

# TWISTED INDEX THEORY ON GOOD ORBIFOLDS, I: NONCOMMUTATIVE BLOCH THEORY

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We study the twisted index theory of elliptic operators on orbifold covering spaces of compact good orbifolds, which are invariant under a projective action of the orbifold fundamental group. We apply these results to obtain qualitative results on real and complex hyperbolic spaces in 2 and 4 dimensions, related to generalizations of the *Bethe-Sommerfeld conjecture* and the *Ten Martini Problem*, on the spectrum of self adjoint elliptic operators which are invariant under a projective action of a discrete cocompact group.

## Introduction

In this paper, we prove a twisted index theorem for elliptic operators on orbifold covering spaces of compact good orbifolds, which are invariant under a projective action of the orbifold fundamental group.

Let  $\Gamma$  be a Fuchsian group of signature  $(g, \nu_1, \dots, \nu_n)$  (cf. section 1 for more details), that is,  $\Gamma$  is the orbifold fundamental group of the 2 dimensional hyperbolic orbifold

$$\Sigma(g, \nu_1, \dots, \nu_n)$$

of signature  $(g, \nu_1, \dots, \nu_n)$ . Using a result of Kasparov <sup>23</sup> on  $K$ -amenable groups as well as a calculation by Farsi <sup>15</sup> of the *orbifold K*-theory of compact 2-dimensional hyperbolic orbifolds, we are able to compute the  $K$ -theory of twisted group  $C^*$  algebras, under the

assumption that the Dixmier-Douady invariant of the multiplier  $\sigma$  is trivial

$$K_j(C^*(\Gamma, \sigma)) \cong \begin{cases} \mathbb{Z}^{2-n+\sum_{i=1}^n \nu_i} & \text{if } j = 0; \\ \mathbb{Z}^{2g} & \text{if } j = 1. \end{cases}$$

Notice that  $K_0$  is much larger in the general Fuchsian group case than in the torsion free case, where  $K_0$  was determined<sup>9</sup> to be always  $\mathbb{Z}^2$ . We also show that the orbifold  $K$ -theory of any 2-dimensional orbifold is generated by orbifold line bundles. The result is derived by means of equivariant  $K$ -theory and the Baum-Connes<sup>4</sup> equivariant Chern character with values in the delocalized equivariant cohomology of the smooth surface  $\Sigma_{g'}$  that covers the good orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$ . We show that the Seifert invariants<sup>37</sup> correspond to the pairing of the equivariant Chern character<sup>4</sup> with a fundamental class in the delocalized equivariant homology of  $\Sigma_{g'}$ .

Let  $tr$  denote the canonical trace on the twisted group  $C^*$ -algebra,  $C^*(\Gamma, \sigma)$ , which induces a map  $[tr]$  on  $K$ -theory. Using the results above and our twisted index theorem for orbifolds, we compute in section 2 under the same assumptions as before, the range of the trace on  $K$ -theory to be,

$$[tr](K_0(C^*(\Gamma, \sigma))) = \mathbb{Z}\theta + \mathbb{Z} + \sum_{i=1}^n \mathbb{Z}(1/\nu_i)$$

where  $\theta$  denotes the evaluation of the multiplier  $\sigma$  on the fundamental class of  $\Gamma$ . We then apply our calculation of the range of the trace on  $K$ -theory to the study of some quantitative aspects of the spectrum of projectively periodic elliptic operators on the hyperbolic plane, what is known as *noncommutative Bloch theory*. Some of the most outstanding open problems about magnetic Schrödinger operators or Hamiltonians on Euclidean space are concerned with the nature of their spectrum, most notably the *Bethe-Sommerfeld conjecture* (BSC) and the *Ten Martini Problem* (TMP)<sup>38</sup>. More precisely, TMP asks whether given a multiplier  $\sigma$  on  $\mathbb{Z}^2$ , is there an associated Hamiltonian (*i.e.* a Hamiltonian which commutes with the  $(\mathbb{Z}^2, \bar{\sigma})$  projective action of  $\mathbb{Z}^2$  on  $L^2(\mathbb{R}^2)$ ) possessing a Cantor set type spectrum, in the sense that the intersection of the spectrum of the Hamiltonian with some compact interval in  $\mathbb{R}$  is a Cantor set? One can deduce from the range of the trace on  $K_0$  of the twisted group  $C^*$ -algebras that when the multiplier takes its values in the roots of unity in  $\mathbf{U}(1)$  (we say then that it is rational) that such a Hamiltonian cannot exist. However, in the Euclidean case and for almost all irrational numbers, the discrete form of TMP has been settled in the affirmative<sup>26</sup>. BSC asserts that if the multiplier is trivial, then the spectrum of any associated Hamiltonian has only a *finite* number of gaps. This was first established in the Euclidean case by Skrigonov<sup>39</sup>. In Sections 2 and 3, we are concerned also with generalizations of the TMP and the BSC, which we call the *Generalized Ten Dry Martini Problem* and the *Generalized Bethe-Sommerfeld conjecture*. We prove that the Kadison constant of the twisted group  $C^*$ -algebra  $C_r^*(\Gamma, \sigma)$  is positive whenever the multiplier is rational, where  $\Gamma$  is now the orbifold fundamental group of a signature  $(g, \nu_1, \dots, \nu_n)$  hyperbolic orbifold. We then use the results of Brüning and Sunada<sup>8</sup> to deduce that when

the multiplier is rational, the generalized Ten Dry Martini Problem is answered in the negative, and we leave open the more difficult irrational case. More precisely, we show that the spectrum of such a  $(\Gamma, \bar{\sigma})$  projectively periodic elliptic operator is the union of countably many (possibly degenerate) closed intervals which can only accumulate at infinity. This also gives evidence that the generalized Bethe-Sommerfeld conjecture is true, and generalizes earlier results<sup>9</sup> in the torsion-free case. In order to show that the results are not a purely two-dimensional phenomenon, we present similar results on real and complex hyperbolic four-manifolds, see also<sup>28</sup>. In section 3, we again use the range of the trace theorem above, together with other geometric arguments to give a complete classification up to isomorphism of the twisted group  $C^*$ -algebras  $C_r^*(\Gamma, \sigma)$ , where  $\sigma$  is assumed to have trivial Dixmier-Douady invariant as before.

In a forthcoming paper we shall generalize these results by proving a twisted higher index theorem which adapts the index theorems of Atiyah, Connes and Moscovici, and Gromov, to the case of good orbifolds. This will allow us to compute the range of some higher traces on  $K$ -theory. More precisely, suppose that  $c$  is the area 2-cocycle on the group  $\Gamma$  as given above, and  $tr_c$  is the induced cyclic 2-cocycle on a smooth subalgebra of the twisted group  $C^*$ -algebra  $C^*(\Gamma, \sigma)$ , which induces a map  $[tr_c]$  on  $K$ -theory. Then we will prove that

$$[tr_c](K_0(C^*(\Gamma, \sigma))) = \phi\mathbb{Z}$$

where  $\phi = 2(g - 1) + (n - \nu) \in \mathbb{Q}$ ,  $\nu = \sum_{j=1}^n 1/\nu_j$ . By relating the hyperbolic Connes-Kubo cyclic 2-cocycle and the area cyclic 2-cocycle, the range of the higher trace on  $K$ -theory can be used to compute the values of the Hall conductance: The results will be applied to the study the occurrence of *fractional quantum numbers* in the Quantum Hall Effect on the hyperbolic plane. We will also establish the noncommutative Bloch theory results for discrete Harper type operators, which is the analogue in the discrete case of results proved in the present paper. The results contained in this paper, together with the results on the fractional quantum numbers, were circulated as a preprint in 1998<sup>27</sup>.

## 1. Preliminaries

### 1.1. Good orbifolds

Further details on the fundamental material on orbifolds can be found in several references<sup>37, 16, 7</sup>. The definition of an orbifold generalizes that of a manifold. More precisely, an *orbifold*  $M$  of dimension  $m$  is a Hausdorff, second countable topological space with a Satake atlas  $\mathcal{V} = \{U_i, \phi_i\}$  which covers  $M$ , consisting of open sets  $U_i$  and homeomorphisms  $\phi_i : U_i \rightarrow D^m/G_i$ , where  $D^m$  denotes the unit ball in  $\mathbb{R}^m$  and  $G_i$  is a finite subgroup of the orthogonal group  $O(m)$ , satisfying the following compatibility relations; the compositions

$$\phi_j \circ \phi_i^{-1} : \phi_i(U_i \cap U_j) \rightarrow \phi_j(U_i \cap U_j)$$

locally lifts to be a smooth map  $\mathbb{R}^m \rightarrow \mathbb{R}^m$ , whenever the intersection  $U_i \cap U_j \neq \emptyset$ . The open sets  $U_i$  are called local orbifold charts. In general, an orbifold  $M$  can be obtained as a quotient  $M = X/G$  of an infinitesimally free compact Lie group action on a smooth manifold  $X$ . In fact, by Satake<sup>36</sup> and Kawasaki<sup>25</sup>,  $X$  can chosen to be the smooth manifold of orthonormal frames of the orbifold tangent bundle of  $M$  (cf. section 1.4) and  $G$  can be chosen to be the orthogonal group  $O(m)$ .

An orbifold covering of  $M$  is an orbifold map  $f : Y \rightarrow M$ , where  $Y$  is also an orbifold, such that any point on  $M$  has a neighborhood  $U$  such that  $f^{-1}(U)$  is the disjoint union of open sets  $U_\alpha$ , with  $f|_{U_\alpha} : U_\alpha \rightarrow U$  a quotient map between two quotients of  $\mathbb{R}^k$  by finite groups  $H_1 < H_2$ . The generic fibers of the covering map  $f$  are isomorphic to a discrete group which acts as deck transformations.

An orbifold  $M$  is *good* if it is orbifold-covered by a smooth manifold; it is *bad* otherwise. A good orbifold is said to be *orientable* if it is orbifold covered by an oriented manifold and the deck transformations act via orientation preserving diffeomorphisms on the orbifold cover. Equivalently, as shown in<sup>36</sup> and<sup>25</sup>, an orbifold is orientable if it has an oriented frame bundle  $X$  such that  $M = X/\mathbf{SO}(m)$ .

We next recall briefly some basic notions on Euclidean and hyperbolic orbifolds, which are by fiat orbifolds whose universal orbifold covering space is Euclidean space and hyperbolic space respectively. We are mainly interested in the case of 2 dimensions, and we will assume that the orbifolds in this paper are orientable.

A 2-dimensional compact orbifold has singularities that are cone points or reflector lines. Up to passing to  $\mathbb{Z}_2$ -orbifold covers, it is always possible to reduce to the case with only isolated cone points.

Let  $\mathbf{H}$  denote the hyperbolic plane and  $\Gamma$  a *Fuchsian group of signature*  $(g, \nu_1, \dots, \nu_n)$ , that is,  $\Gamma$  is a discrete cocompact subgroup of  $\mathbf{PSL}(2, \mathbb{R})$  of genus  $g$  and with  $n$  elliptic elements of order  $\nu_1, \dots, \nu_n$  respectively. Explicitly,

$$\begin{aligned} \Gamma = & \left\{ A_i, B_i, C_j \in \mathbf{PSL}(2, \mathbb{R}) \mid i = 1, \dots, g, \quad j = 1, \dots, n, \right. \\ & \left. \prod_{i=1}^g [A_i, B_i] C_1 \dots C_n = 1, \quad C_j^{\nu_j} = 1, \quad j = 1, \dots, n \right\} \end{aligned}$$

Then the corresponding compact oriented hyperbolic 2-orbifold of signature  $(g, \nu_1, \dots, \nu_n)$  is defined as the quotient space

$$\Sigma(g, \nu_1, \dots, \nu_n) = \Gamma \backslash \mathbf{H}.$$

A compact oriented 2-dimensional Euclidean orbifold is obtained in a similar manner, but with  $\mathbf{H}$  replaced by  $\mathbb{R}^2$ , and a complete list of these can be found in<sup>37</sup>.

Then  $\Sigma(g, \nu_1, \dots, \nu_n)$  is a compact surface of genus  $g$  with  $n$  elliptic points  $\{p_j\}_{j=1}^n$  such that each  $p_j$  has a small coordinate neighborhood  $U_{p_j} \cong D^2 / \mathbb{Z}_{\nu_j}$ , where  $D^2$  denotes the unit disk in  $\mathbb{R}^2$  and  $\mathbb{Z}_{\nu_j}$  is the cyclic group of order  $\nu_j$ ,  $j = 1, \dots, n$ . Observe

that the complement  $\Sigma(g, \nu_1, \dots, \nu_n) \setminus \cup_{j=1}^n U_{p_j}$  is a compact Riemann surface of genus  $g$  and with  $n$  boundary components. The group  $\Gamma$  is the orbifold fundamental group of  $\Sigma(g, \nu_1, \dots, \nu_n)$ , where the generators  $C_j$  can be represented by the  $n$  boundary components of the surface  $\Sigma(g, \nu_1, \dots, \nu_n) \setminus \cup_{j=1}^n U_{p_j}$ .

All Euclidean and hyperbolic 2-dimensional orbifolds  $\Sigma(g, \nu_1, \dots, \nu_n)$  are good, being in fact orbifold covered by a smooth surface  $\Sigma_{g'}$  cf. <sup>37</sup>, i.e. there is a finite group  $G$  acting on  $\Sigma_{g'}$  with quotient  $\Sigma(g, \nu_1, \dots, \nu_n)$ , where

$$g' = 1 + \frac{\#(G)}{2}(2(g-1) + (n-\nu))$$

and where  $\nu = \sum_{j=1}^n 1/\nu_j$ . According to the classification of 2-dimensional orbifolds given in <sup>37</sup>, the only bad 2-orbifolds are the “teardrop”, with underlying surface  $S^2$  and one cone point of cone angle  $2\pi/p$ , and the “double teardrop”, with underlying surface  $S^2$  and two cone points with angles  $2\pi/p$  and  $2\pi/q$ ,  $p \neq q$ .

In this paper we restrict our attention to good orbifolds. It should be pointed out that the techniques used in this paper cannot be extended directly to the case of bad orbifolds. It is reasonable to expect that the index theory on bad orbifolds will involve analytical techniques for more general conic type singularities.

## 1.2. Twisted $C^*$ algebras

We begin by recalling the definitions of the (reduced) twisted group  $C^*$  algebra and its relation to a twisted  $C^*$  algebra of bounded operators on the universal orbifold cover of a good orbifold, that was defined in <sup>8</sup>.

Let  $\Gamma$  be a discrete group and  $\sigma$  be a *multiplier* on  $\Gamma$ , i.e.  $\sigma : \Gamma \times \Gamma \rightarrow \mathbf{U}(1)$  is a  $\mathbf{U}(1)$ -valued 2-cocycle on the group  $\Gamma$  i.e.  $\sigma$  satisfies the following identity:

- $\sigma(\gamma, 1) = \sigma(1, \gamma) = 1 \quad \forall \gamma \in \Gamma;$
- $\sigma(\gamma_1, \gamma_2)\sigma(\gamma_1\gamma_2, \gamma_3) = \sigma(\gamma_1, \gamma_2\gamma_3)\sigma(\gamma_2, \gamma_3) \quad \forall \gamma_1, \gamma_2, \gamma_3 \in \Gamma.$

Consider the Hilbert space of square summable functions on  $\Gamma$ ,

$$L^2(\Gamma) = \left\{ f : \Gamma \rightarrow \mathbb{C} \mid \sum_{\gamma \in \Gamma} |f(\gamma)|^2 < \infty \right\}.$$

There are natural left  $\sigma$ -regular and right  $\sigma$ -regular representations on  $L^2(\Gamma)$ . The *left  $\sigma$ -regular representation* is defined as follows:  $\forall \gamma, \gamma' \in \Gamma$ ,

$$\begin{aligned} (L_\gamma^\sigma f)(\gamma') &= f(\gamma^{-1}\gamma')\sigma(\gamma, \gamma^{-1}\gamma'); \\ L_\gamma^\sigma L_{\gamma'}^\sigma &= \sigma(\gamma, \gamma')L_{\gamma\gamma'}^\sigma. \end{aligned}$$

The *right  $\sigma$ -regular representation* is defined as follows:  $\forall \gamma, \gamma' \in \Gamma$ ,

$$\begin{aligned} (R_\gamma^\sigma f)(\gamma') &= f(\gamma'\gamma)\sigma(\gamma', \gamma); \\ R_\gamma^\sigma R_{\gamma'}^\sigma &= \sigma(\gamma, \gamma')R_{\gamma\gamma'}^\sigma. \end{aligned}$$

One can use the cocycle identity to show that the left  $\sigma$ -regular representation commutes with the right  $\bar{\sigma}$ -regular representation, where  $\bar{\sigma}$  denotes the conjugate cocycle. Also the left  $\bar{\sigma}$ -regular representation commutes with the right  $\sigma$ -regular representation. Define

$$W^*(\Gamma, \sigma) = \{ A \in B(\ell^2(\Gamma)) : [L_\gamma^{\bar{\sigma}}, A] = 0 \ \forall \gamma \in \Gamma \}$$

i.e.  $W^*(\Gamma, \sigma)$  is the commutant of the left  $\bar{\sigma}$ -regular representation. By general theory, it is a von Neumann algebra, and it is called the *twisted group von Neumann algebra*. It can also be realized in the following manner: the right  $\sigma$ -regular representation of  $\Gamma$  extends to a \* representation of the twisted group algebra,  $\mathbb{C}(\Gamma, \sigma) \rightarrow B(\ell^2(\Gamma))$ . Now the *weak closure* (which coincides with the strong closure) of  $\mathbb{C}(\Gamma, \sigma)$  also yields the twisted group von Neumann algebra  $W^*(\Gamma, \sigma)$ , by the commutant theorem of von Neumann. The *norm closure* of  $\mathbb{C}(\Gamma, \sigma)$  yields the (reduced) *twisted group  $C^*$  algebra*  $C_r^*(\Gamma, \sigma)$ . We will also briefly consider the full or unreduced *twisted group  $C^*$  algebra*  $C^*(\Gamma, \sigma)$ , which is another  $C^*$  completion of  $\mathbb{C}(\Gamma, \sigma)$  using \*-representations, cf. <sup>31</sup> for the definition.

Let  $M$  be a good, compact orbifold, and  $\mathcal{E} \rightarrow M$  be an orbifold vector bundle over  $M$ , and  $\tilde{\mathcal{E}} \rightarrow \tilde{M}$  be its lift to the universal orbifold covering space  $\Gamma \rightarrow \tilde{M} \rightarrow M$ , which is by assumption a simply-connected smooth manifold. We will now briefly review how to construct a  $(\Gamma, \bar{\sigma})$ -action (where  $\sigma$  is a multiplier on  $\Gamma$  and  $\bar{\sigma}$  denotes its complex conjugate) on  $L^2(\tilde{M})$ . Let  $\omega = d\eta$  be an exact 2-form on  $\tilde{M}$  such that  $\omega$  is also  $\Gamma$ -invariant, although  $\eta$  is *not* assumed to be  $\Gamma$ -invariant. Define a Hermitian connection on the trivial line bundle over  $\tilde{M}$  as

$$\nabla = d + i\eta.$$

Its curvature is  $\nabla^2 = i\omega$ . Then  $\nabla$  defines a  $(\Gamma, \bar{\sigma})$  action on  $L^2(\tilde{M}, \widetilde{\mathcal{S}^\pm \otimes E})$  as follows:

Since  $\omega$  is  $\Gamma$  invariant, one has  $\forall \gamma \in \Gamma$

$$0 = \gamma^* \omega - \omega = d(\gamma^* \eta - \eta),$$

so that  $\gamma^* \eta - \eta$  is a closed 1-form on a simply-connected manifold  $\tilde{M} \Rightarrow \gamma^* \eta - \eta = d\psi_\gamma$  for some smooth function  $\psi_\gamma$  on  $\tilde{M}$  satisfying

- $\psi_\gamma(x) + \psi_{\gamma'}(\gamma x) - \psi_{\gamma'\gamma}(x)$  is independent of  $x \forall x \in \tilde{M}$ ;
- $\psi_\gamma(x_0) = 0$  for some  $x_0 \in \tilde{M} \ \forall \gamma \in \Gamma$ .

Then  $\bar{\sigma}(\gamma, \gamma') = \exp(i\psi_\gamma(\gamma' x_0))$  defines a multiplier on  $\Gamma$ . Now define the  $(\Gamma, \bar{\sigma})$  action as follows: For  $u \in L^2(\tilde{M}, \widetilde{\mathcal{S}^\pm \otimes E})$ ,  $U_\gamma u = \gamma^* u$ ,  $S_\gamma u = \exp(i\psi_\gamma) u$ , define  $T_\gamma = U_\gamma \circ S_\gamma$ . Then it satisfies  $T_{\gamma_1} T_{\gamma_2} = \bar{\sigma}(\gamma_1, \gamma_2) T_{\gamma_1 \gamma_2}$ , and so it defines a  $(\Gamma, \bar{\sigma})$ -action. It can be shown that only multipliers  $\bar{\sigma}$  such that the Dixmier-Douady invariant  $\delta(\bar{\sigma}) = 0$  can give rise to  $(\Gamma, \bar{\sigma})$ -actions in this way cf. section 2.2 for a further discussion.

Let  $D : L^2(\tilde{M}, \tilde{\mathcal{E}}) \rightarrow L^2(\tilde{M}, \tilde{\mathcal{E}})$  be a self adjoint elliptic differential operator that commutes with a  $(\Gamma, \bar{\sigma})$ -action  $T_\gamma \quad \forall \gamma \in \Gamma$  on  $L^2(\tilde{M}, \tilde{\mathcal{E}})$ . Then by the functional calculus, all the spectral projections of  $D$ ,  $E_\lambda = \chi_{[0, \lambda]}(D)$  are bounded self adjoint operators on

$L^2(\widetilde{M}, \widetilde{\mathcal{E}})$  that commute with  $T_\gamma \quad \forall \gamma \in \Gamma$ . Now the commutant of the  $(\Gamma, \bar{\sigma})$ -action on  $L^2(\widetilde{M}, \widetilde{\mathcal{E}})$  is a von Neumann algebra

$$W^*(\sigma) = \left\{ Q \in B(L^2(\widetilde{M}, \widetilde{\mathcal{E}})) \mid T_\gamma Q = QT_\gamma \quad \forall \gamma \in \Gamma \right\}.$$

Since  $T_\gamma Q = QT_\gamma$ , one sees that

$$e^{-i\phi_\gamma(x)} k_Q(\gamma x, \gamma y) e^{i\phi_\gamma(y)} = k_Q(x, y)$$

$\forall x, y \in \widetilde{M} \quad \forall \gamma \in \Gamma$ , where  $k_Q$  denotes the Schwartz kernel of  $Q$ . In particular, observe that  $\underline{tr}(k_Q(x, x))$  is a  $\Gamma$ -invariant function on  $\widetilde{M}$ , where  $\underline{tr}$  denotes the pointwise trace. Using this, one sees that there is a semi-finite trace on this von Neumann algebra

$$tr : W^*(\sigma) \rightarrow \mathbb{C}$$

defined as in the untwisted case due to Atiyah <sup>1</sup>,

$$Q \rightarrow \int_M \underline{tr}(k_Q(x, x)) dx$$

where  $k_Q$  denotes the Schwartz kernel of  $Q$ . Note that this trace is finite whenever  $k_Q$  is continuous in a neighborhood of the diagonal in  $\widetilde{M} \times \widetilde{M}$ .

By elliptic regularity, the spectral projection  $E_\lambda$  has a smooth Schwartz kernel, so that in particular, the spectral density function,  $N_Q(\lambda) = tr(E_\lambda) < \infty \quad \forall \lambda$ , is well defined.

If  $\mathcal{F}$  is a relatively compact fundamental domain in  $\widetilde{M}$  for the action of  $\Gamma$  on  $\widetilde{M}$ , then one sees that there is a  $(\Gamma, \bar{\sigma})$ -isomorphism

$$L^2(\widetilde{M}, \widetilde{\mathcal{E}}) \cong L^2(\Gamma) \otimes L^2(\mathcal{F}, \widetilde{\mathcal{E}}|_{\mathcal{F}}) \tag{1.1}$$

It is given by  $f \mapsto g$  where  $g(\gamma)(x) = f(\gamma x)$ ,  $x \in \mathcal{F}$ ,  $\gamma \in \Gamma$ , equivalently by a choice of a bounded measurable almost everywhere smooth section of the orbifold covering  $\widetilde{M} \rightarrow M$ . The  $(\Gamma, \bar{\sigma})$ -action on  $L^2(\mathcal{F}, \widetilde{\mathcal{E}}|_{\mathcal{F}})$  is trivial and its is the previously defined regular  $(\Gamma, \bar{\sigma})$ -representation on  $L^2(\Gamma)$ . Therefore

$$W^*(\sigma) \cong W^*(\Gamma, \sigma) \otimes B(L^2(\mathcal{F}, \widetilde{\mathcal{E}}|_{\mathcal{F}}))$$

where  $B(L^2(\mathcal{F}, \widetilde{\mathcal{E}}|_{\mathcal{F}}))$  denotes the algebra of all bounded operators on the Hilbert space  $L^2(\mathcal{F}, \widetilde{\mathcal{E}}|_{\mathcal{F}})$ . There is a natural subalgebra  $C^*(\sigma)$  of  $W^*(\sigma)$  which is defined as follows. Let

$$C_c^\infty(\sigma) = \left\{ Q \in W^*(\sigma) \mid \begin{array}{l} k_Q \text{ is smooth and supported in a compact} \\ \text{neighborhood of the diagonal} \end{array} \right\}$$

Then  $C^*(\sigma)$  is defined to be the *norm closure* of  $C_c^\infty(\sigma)$ . It can also be shown to be the norm closure of

$$\left\{ Q \in W^*(\sigma) \mid \begin{array}{l} k_Q \text{ is smooth and } k_Q(x, y) \text{ is } L^1 \text{ in both} \\ \text{the } x \text{ and } y \text{ variables separately} \end{array} \right\}$$

That is, elements of  $C^*(\sigma)$  are elements of  $W^*(\sigma)$  that have the additional property of some off-diagonal decay. Via the isomorphism given in equation (1.1), it can be shown that

$$C^*(\sigma) \cong C_r^*(\Gamma, \sigma) \otimes \mathcal{K} \quad (1.2)$$

where  $\mathcal{K} = \mathcal{K}(L^2(\mathcal{F}, \tilde{\mathcal{E}}|_{\mathcal{F}}))$  denotes the  $C^*$  algebra of compact operators on the Hilbert space  $L^2(\mathcal{F}, \tilde{\mathcal{E}}|_{\mathcal{F}})$  (see <sup>8</sup> for details).

### 1.3. The $C^*$ algebra of an orbifold

Let  $M$  be an oriented orbifold of dimension  $m$ , that is  $M = P/\mathbf{SO}(m)$ , where  $P$  is the bundle of oriented frames on the orbifold tangent bundle (cf. section 1.4). Then the  $C^*$  algebra of the orbifold  $M$  is by fiat the crossed product  $C^*(M) = C(P) \rtimes \mathbf{SO}(m)$ , where  $C(P)$  denotes the  $C^*$  algebra of continuous functions on  $P$ . We will now study some Morita equivalent descriptions of  $C^*(M)$  that will be useful for us later. The following is one such, and is due to <sup>15</sup>.

**Proposition 1.1** *Let  $M$  be a good orbifold, which is orbifold covered by the smooth manifold  $X$ , i.e.  $M = X/G$ . Then the  $C^*$  algebras  $C_0(X) \rtimes G$  and  $C^*(M)$  are strongly Morita equivalent.*

In the two dimensional case, there is yet another  $C^*$  algebra that is strongly Morita equivalent to the  $C^*$  algebra of the orbifold. Let  $\Gamma$  be as before. Then  $\Gamma$  acts freely on  $\mathbf{PSL}(2, \mathbb{R})$ , and therefore the quotient space

$$\Gamma \backslash \mathbf{PSL}(2, \mathbb{R}) = P(g, \nu_1, \dots, \nu_n)$$

is a smooth compact manifold, with a right action of  $\mathbf{SO}(2)$  that is only infinitesimally free. The  $C^*$  algebra of the hyperbolic orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$  is by fiat the crossed product  $C^*$  algebra

$$C^*(\Sigma(g, \nu_1, \dots, \nu_n)) = C(P(g, \nu_1, \dots, \nu_n)) \rtimes \mathbf{SO}(2)$$

cf. <sup>11</sup>. If  $\mathbf{SO}(2)$  did act freely on  $P(g, \nu_1, \dots, \nu_n)$  (which is the case when  $\nu_1 = \dots = \nu_n = 1$ ), then it is known that  $C^*(\Sigma(g, \nu_1, \dots, \nu_n))$  and  $C(\Sigma(g, \nu_1, \dots, \nu_n))$  are strongly Morita equivalent as  $C^*$  algebras.

We shall next describe a natural algebra which is Morita equivalent to the  $C^*$  algebra of the orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$ . Now  $\Gamma$  has a torsion free subgroup  $\Gamma_{g'}$  of finite index, such that the quotient  $\Gamma_{g'} \backslash \mathbf{H} = \Gamma_{g'} \backslash \mathbf{PSL}(2, \mathbb{R}) / \mathbf{SO}(2) = \Sigma_{g'}$  is a compact Riemann surface of genus  $g' = 1 + \frac{\#(G)}{2}(2(g-1) + (n-\nu))$  where  $\nu = \sum_{j=1}^n 1/\nu_j$ , cf. Theorem 2.5 <sup>37</sup>, and the orbifold Euler characteristic calculations in there. Then  $G \rightarrow \Sigma_{g'} \rightarrow \Sigma(g, \nu_1, \dots, \nu_n)$  is a finite orbifold cover, i.e. a ramified covering space, where  $G = \Gamma_{g'} \backslash \Gamma$ .

**Proposition 1.2** *The  $C^*$  algebras  $C(\Sigma_{g'}) \rtimes G$ ,  $C^*(\Sigma(g, \nu_1, \dots, \nu_n))$  and  $C_0(\mathbf{H}) \rtimes \Gamma$  are strongly Morita equivalent to each other.*

**Proof.** The strong Morita equivalence of the last two  $C^*$  algebras is contained in the previous Proposition. Since strong Morita equivalence is an equivalence relation, it suffices to prove that the first two  $C^*$  algebras are strongly Morita equivalent. Let

$$\widehat{P} = \Gamma_{g'} \backslash \mathbf{PSL}(2, \mathbb{R})$$

where  $\mathbf{SO}(2)$  acts on  $\widehat{P}$  the right, and therefore commutes with the left  $G$  action on  $\widehat{P}$ . Moreover, the actions of  $G$  and  $\mathbf{SO}(2)$  on  $\widehat{P}$  are free, and therefore one can apply a theorem of Green,<sup>19</sup> which implies in particular that  $C_o(G \backslash \widehat{P}) \rtimes \mathbf{SO}(2)$  and  $C_o(\widehat{P}/\mathbf{SO}(2)) \rtimes G$  are strongly Morita equivalent, i.e.  $C_o(P(g, \nu_1, \dots, \nu_n)) \rtimes \mathbf{SO}(2)$  and  $C_o(\Sigma_{g'}) \rtimes G$  are strongly Morita equivalent, proving the proposition.  $\diamond$

#### 1.4. Orbifold vector bundles and K-theory

Because of the Morita equivalences of the last section 1.3, we can give several alternate and equivalent descriptions of orbifold vector bundles over orbifolds. Firstly, there is the description using transition functions cf.<sup>36, 25</sup>. Equivalently, one can view an orbifold vector bundle over an  $m$  dimensional orbifold  $M$  as being an  $\mathbf{SO}(m)$  equivariant vector bundle over the bundle  $P$  of oriented frames of the orbifold tangent bundle. In the case of a good orbifold  $M$ , which is orbifold covered by a smooth manifold  $X$ , let  $G$  be the discrete group acting on  $X$ ,  $G \rightarrow X \rightarrow M = X/G$ . Then an orbifold vector bundle on  $M$  is the quotient  $\mathcal{V}_M = G \backslash \mathcal{V}_X$  of a vector bundle over  $X$  by the  $G$  action. Notice that an orbifold vector bundle is not a vector bundle over  $M$ : in fact, the fiber at a singular point is isomorphic to a quotient of a vector space by a finite group action.

The Grothendieck group of isomorphism classes of orbifold vector bundles on the orbifold  $M$  is called the *orbifold K-theory* of  $M$  and is denoted by  $K_{orb}^0(M)$ , which by a result of<sup>4, 15</sup> is canonically isomorphic to  $K_0(C^*(M))$ . By the Morita equivalence of section 1.3, one then has  $K_{orb}^0(M) \cong K_{\mathbf{SO}(m)}^0(P)$ , and by the Julg-Green theorem<sup>21, 19</sup>, the second group is isomorphic to  $K_0(C(P) \rtimes \mathbf{SO}(m))$ . In the case when  $M$  is a good orbifold, by Proposition 1.1, one sees that  $K_{orb}^0(M) \cong K^0(C_0(X) \rtimes G) = K_G^0(X)$ .

We will now be mainly interested in orbifold line bundles over hyperbolic 2-orbifolds. Let  $G$  be the finite group determined by the exact sequence

$$1 \rightarrow \Gamma_{g'} \rightarrow \Gamma \rightarrow G \rightarrow 1.$$

Then  $G$  acts on  $\Sigma_{g'}$  with quotient the orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$ .

An orbifold line bundle  $\mathcal{L}$  on  $\Sigma(g, \nu_1, \dots, \nu_n)$  is given by

$$\mathcal{L} = G \backslash (P \times_{\mathbf{SO}(2)} \mathbb{C}),$$

where  $P$  is a principal  $\mathbf{SO}(2)$ -bundle on the smooth surface  $\Sigma_{g'}$ . Notice that the  $\mathbf{SO}(2)$  and the  $G$  actions commute, and are free on the total space  $P$ . An orbifold line bundle has

an associated Seifert fibered space  $G \setminus P$ . A more explicit local geometric construction of  $\mathcal{L}$  is given in <sup>37</sup>. An orbifold line bundle  $\mathcal{L}$  over a hyperbolic orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$  is specified by the Chern class of the pullback line bundle on the smooth surface  $\Sigma_{g'}$ , together with the Seifert data. That is the pairs of numbers  $(\beta_j, \nu_j)$ , where  $\beta_j$  satisfies the following condition. Given the exact sequence

$$1 \rightarrow \mathbb{Z} \rightarrow \pi_1(P) \rightarrow \pi_1^{orb}(\Sigma(g, \nu_1, \dots, \nu_n)) \rightarrow 1,$$

let  $\tilde{C}_j$  be an element of  $\pi_1(P)$  that maps to the generator  $C_j$  of the orbifold fundamental group. Let  $C$  be the generator of the fundamental group of the fiber. Then we have  $C_j^{\nu_j} = 1$  and  $C^{\beta_j} = \tilde{C}_j^{\nu_j}$ . The choice of  $\beta_j$  can be normalized so that  $0 < \beta_j < \nu_j$ .

More geometrically, let  $\Sigma(g, \nu_1, \dots, \nu_n)$  be a hyperbolic orbifold with the cone points  $p_1, \dots, p_n$ . Let  $\Sigma'$  be the complement of the union of small disks around the cone points. The orbifold line bundle induces a line bundle  $\mathcal{L}'$  over the smooth surface with boundary  $\Sigma'$ , trivialized over the boundary components of  $\Sigma'$ . Moreover, the restriction of the orbifold line bundle  $\mathcal{L}$  over the small disks  $D_{p_i}$  around each cone point  $p_i$  is obtained by considering a surgery on the trivial product  $\mathbb{C} \times D_{p_i}$  obtained by cutting open along a radius in  $\mathbb{C}$  and gluing back after performing a rotation on  $D_{p_i}$  by an angle  $2\pi q/\nu_i$ . With this notation the Seifert invariants are  $(q_i, \nu_i)$  with  $\beta_i q_i \equiv 1 \pmod{\nu_i}$ .

Thus, an orbifold line bundle has a finite set of singular fibers at the cone points. The orbifold line bundle  $\mathcal{L}$  pulls back to a  $G$ -equivariant line bundle  $\tilde{\mathcal{L}}$  over the smooth surface  $\Sigma_{g'}$  that orbifold covers  $\Sigma(g, \nu_1, \dots, \nu_n)$ . All the orbifold line bundles with trivial orbifold Euler class, as defined in <sup>37</sup>, lift to the trivial line bundle on  $\Sigma_{g'}$ .

In <sup>37</sup> the classification of Seifert-fibered spaces is derived using the Seifert invariants, namely the Chern class of the line bundle  $\tilde{\mathcal{L}}$ , together with the Seifert data  $(\beta_j, \nu_j)$  of the singular fibers at the cone points  $p_j$ . We show in the following that the Seifert invariants can be recovered from the image of the Baum-Connes equivariant Chern character <sup>4</sup>.

### 1.5. Baum-Connes Chern character

We have seen that the algebra  $C^*(\Sigma(g, \nu_1, \dots, \nu_n))$  is strongly Morita equivalent to the cross product  $C(\Sigma_{g'}) \rtimes G$ . Therefore the relevant K-theory is

$$K_0(C(\Sigma_{g'}) \rtimes G) = K_{\mathbf{SO}(2)}^0(G \setminus \hat{P}) = K_G^0(\Sigma_{g'}),$$

where  $\hat{P} = \Gamma_{g'} \setminus \mathbf{PSL}(2, \mathbb{R})$ .

We recall briefly the definition of delocalized equivariant cohomology for a finite group action on a smooth manifold <sup>4</sup>. Let  $G$  be a finite group acting smoothly and properly on a compact smooth manifold  $X$ . Let  $M$  be the good orbifold  $M = G \setminus X$ . Given any  $\gamma \in G$ , the subset  $X^\gamma$  of  $X$  given by

$$X^\gamma = \{(x, \gamma) \in X \times G \mid \gamma x = x\}$$

is a smooth compact submanifold. Let  $\widehat{X}$  be the disjoint union of the  $X^\gamma$  for  $\gamma \in G$ . The complex  $\Omega_G(\widehat{X})$  of  $G$ -invariant de Rham forms on  $\widehat{X}$  with coefficients in  $\mathbb{C}$  computes the delocalized equivariant cohomology  $H^\bullet(X, G)$ , which is  $\mathbb{Z}_2$  graded by forms of even and odd degree. The dual complex that computes delocalized homology is obtained by considering  $G$ -invariant de Rham currents on  $\widehat{X}$ . Thus we have

$$\begin{aligned} H^\bullet(X, G) &= H^\bullet(\Omega_G(\widehat{X}), d) = H^\bullet(\widehat{X}/G, \mathbb{C}) \\ &= H^\bullet(\widehat{X}, \mathbb{C})^G = \bigoplus_{\gamma \in G} H^\bullet(X^\gamma, \mathbb{C}). \end{aligned}$$

According to <sup>4</sup>, Theorem 7.14, the delocalized equivariant cohomology is isomorphic to the cyclic cohomology of the algebra  $C^\infty(X) \rtimes G$ ,

$$\begin{aligned} H^0(X, G) &\cong HC^{ev}(C^\infty(X) \rtimes G), \\ H^1(X, G) &\cong HC^{odd}(C^\infty(X) \rtimes G). \end{aligned}$$

The Baum-Connes equivariant Chern character

$$ch_G : K_G^0(X) \rightarrow H^0(X, G)$$

is an isomorphism over the complex numbers. Equivalently, the Baum-Connes equivariant Chern character can be viewed as

$$ch_G : K_{orb}^0(M) \rightarrow H_{orb}^0(M)$$

where the *orbifold cohomology* is by definition  $H_{orb}^j(M) = H^j(X, G)$  for  $j = 0, 1$ .

In our case the delocalized equivariant cohomology and the Baum-Connes Chern character have a simple expression. In fact, let  $\Sigma_{g'}$  be the smooth surface that orbifold covers  $\Sigma(g, \nu_1, \dots, \nu_n)$ . Let  $G$  be the finite group  $1 \rightarrow \Gamma_{g'} \rightarrow \Gamma \rightarrow G \rightarrow 1$ . Let  $G_{p_j} \cong \mathbb{Z}_{\nu_j}$  be the stabilizer of the cone point  $p_j$  in  $\Sigma(g, \nu_1, \dots, \nu_n)$ . Then we have

$$\Sigma_{g'}^\gamma = \begin{cases} \Sigma_{g'} & \text{if } \gamma = 1; \\ \{p_j\} & \text{if } \gamma \in G_{p_j} \setminus \{1\}; \\ \emptyset & \text{otherwise.} \end{cases}$$

Thus the delocalized equivariant cohomology and orbifold cohomology is given by

$$H_{orb}^0(\Sigma(g, \nu_1, \dots, \nu_n)) = H^0(\Sigma_{g'}, G) = H^0(\Sigma_{g'}) \oplus H^2(\Sigma_{g'}) \oplus \mathbb{C}^{\sum_j (\nu_j - 1)},$$

where each  $\mathbb{C}^{\nu_j - 1}$  is given by  $\nu_j - 1$  copies of  $H^0(p_j)$ , and

$$H_{orb}^1(\Sigma(g, \nu_1, \dots, \nu_n)) = H^1(\Sigma_{g'}, G) = H^1(\Sigma_{g'}).$$

Let  $\mathcal{L}$  be an orbifold line bundle in  $K_0(C(\Sigma_g) \rtimes G) = K_G^0(\Sigma_g)$ , and let  $\tilde{\mathcal{L}}$  be the corresponding line bundle over the surface  $\Sigma_{g'}$ . An element  $\gamma$  in the stabilizer  $G_{p_j}$  acts on the restriction of  $\mathcal{L}|_{\Sigma_g^\gamma} = \mathcal{L}|_{p_j} = \mathbb{C}$  as multiplication by  $\lambda(\gamma) = e^{2\pi i \beta_j / \nu_j}$ .

Thus, the Baum-Connes Chern character of  $\mathcal{L}$  is given by

$$ch_G(\mathcal{L}) = (1, c_1(\tilde{\mathcal{L}}), e^{2\pi i \beta_1/\nu_1}, \dots, e^{2\pi i (\nu_1-1)\beta_1/\nu_1}, \dots, e^{2\pi i \beta_n/\nu_n}, \dots, e^{2\pi i (\nu_n-1)\beta_n/\nu_n}).$$

**Proposition 1.3** *The Baum-Connes Chern character classifies orbifold line bundles over the orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$ .*

**Proof.** According to <sup>37</sup> the orbifold line bundles are classified by the orbifold Euler number

$$e(\Sigma(g, \nu_1, \dots, \nu_n)) = < c_1(\tilde{\mathcal{L}}), [\Sigma_{g'}] > + \sum_j \beta_j / \nu_j,$$

given in terms of the Chern number  $< c_1(\tilde{\mathcal{L}}), [\Sigma_{g'}] >$  and the Seifert invariants  $(\beta_j, \nu_j)$ .  $\diamond$

Notice that we have the isomorphism in  $K$ -theory,  $K_G^0(\Sigma_{g'}) = K_{\mathbf{SO}(2)}^0(G \setminus \widehat{P})$  and the Chern character isomorphisms (with  $\mathbb{C}$  coefficients)

$$ch_G : K_G^0(\Sigma_{g'}) \rightarrow H^0(\Sigma_{g'}, G) \cong HC^{ev}(C^\infty(\Sigma_{g'}) \rtimes G)$$

and

$$ch_{\mathbf{SO}(2)} : K_{\mathbf{SO}(2)}^0(\Gamma \setminus \mathbf{PSL}(2, \mathbb{R})) \rightarrow HC^{ev}(C^\infty(\Gamma \setminus \mathbf{PSL}(2, \mathbb{R})) \rtimes \mathbf{SO}(2)).$$

Moreover, we have an isomorphism

$$HC^\bullet(C^\infty(\Gamma \setminus \mathbf{PSL}(2, \mathbb{R})) \rtimes \mathbf{SO}(2)) \cong H_{\mathbf{SO}(2)}^\bullet(\Gamma \setminus \mathbf{PSL}(2, \mathbb{R})).$$

Thus, we obtain

$$HC^{ev}(C^\infty(\Gamma \setminus \mathbf{PSL}(2, \mathbb{R})) \rtimes \mathbf{SO}(2)) \cong HC^{ev}(C^\infty(\Sigma_{g'}) \rtimes G)$$

with  $\mathbb{C}$  coefficients, via the Chern character.

Thus orbifold line bundles on  $\Sigma(g, \nu_1, \dots, \nu_n)$  can be also described as  $G$ -equivariant line bundles over the covering smooth surface  $\Sigma_{g'}$ , and again as  $\mathbf{SO}(2)$ -equivariant line bundles on  $G \setminus \widehat{P}$ .

**Remarks 1.4** With the notation used in the previous section, let  $G$  be a finite group acting smoothly and properly on a smooth compact oriented manifold  $X$ . There is a natural choice of a fundamental class  $[X]_G \in H_0(X, G)$  in the delocalized equivariant homology of  $X$ , given by the fundamental classes of each compact oriented smooth submanifold  $X^\gamma$ ,  $[X]_G = \bigoplus_{\gamma \in G} [X^\gamma]$ . In the case of hyperbolic 2-orbifolds, the equivariant fundamental class  $[\Sigma_{g'}]_G$  is given by

$$[\Sigma_{g'}]_G = [\Sigma_{g'}] \oplus_j [p_j]^{\nu_j-1} \in H_2(\Sigma_{g'}, \mathbb{C}) \oplus_j (H_0(p_j, \mathbb{C}))^{\nu_j-1}.$$

The corresponding equivariant Euler number  $< ch_G(\mathcal{L}), [\Sigma_{g'}]_G >$  is obtained by evaluating

$$< ch_G(\mathcal{L}), [\Sigma_{g'}]_G > = < c_1(\tilde{\mathcal{L}}), [\Sigma_{g'}] > + \sum_{j=1}^n \sum_{\gamma \in G_{p_j} \setminus \{1\}} \lambda(\gamma).$$

### 1.6. Classifying space of the orbifold fundamental group

Here we find it convenient to follow Baum, Connes and Higson<sup>4, 5</sup>. Let  $M$  be a good orbifold, that is its orbifold universal cover  $\widetilde{M}$  is a smooth manifold which has a *proper*  $\Gamma$ -action, where  $\Gamma$  denotes the orbifold fundamental group of  $M$ . That is, the map

$$\begin{aligned}\widetilde{M} \times \Gamma &\rightarrow \widetilde{M} \times \widetilde{M} \\ (x, \gamma) &\rightarrow (x, \gamma x)\end{aligned}$$

is a proper map. The universal example for such a proper action is denoted in<sup>4, 5</sup> by  $\underline{E}\Gamma$ . It is universal in the sense that there is a continuous  $\Gamma$ -map

$$f : \widetilde{M} \rightarrow \underline{E}\Gamma$$

which is unique up to  $\Gamma$ -homotopy, and moreover  $\underline{E}\Gamma$  itself is unique up to  $\Gamma$ -homotopy. The quotient  $\underline{B}\Gamma = \Gamma \backslash \underline{E}\Gamma$  is an orbifold. Just as  $B\Gamma$  classifies isomorphism classes of  $\Gamma$ -covering spaces, it can be shown that  $\underline{B}\Gamma$  classifies isomorphism classes of orbifold  $\Gamma$ -covering spaces.

**Examples 1.5** It turns out that if  $\Gamma$  is a discrete subgroup of a connected Lie group  $G$ , then  $\underline{E}\Gamma = G/K$ , where  $K$  is a maximal compact subgroup.

**Examples 1.6** The orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$ , viewed as the quotient space

$$\Sigma(g, \nu_1, \dots, \nu_n) = \Gamma \backslash \mathbf{H}$$

is an example of the above construction.

This is the main class of examples that we are concerned with in this paper.

Let  $S\Gamma$  denote the set of all elements of  $\Gamma$  which are of finite order. Then  $S\Gamma$  is not empty, since  $1 \in S\Gamma$ .  $\Gamma$  acts on  $S\Gamma$  by conjugation, and let  $F\Gamma$  denote the associated permutation module over  $\mathbb{C}$ , i.e.

$$F\Gamma = \left\{ \sum_{\alpha \in S\Gamma} \lambda_\alpha [\alpha] \mid \lambda_\alpha \in \mathbb{C} \text{ and } \lambda_\alpha = 0 \text{ except for a finite number of } \alpha \right\}$$

### 1.7. Twisting an elliptic operator

We will discuss elliptic operators only on good orbifolds, and refer to<sup>25</sup> for the general case. Let  $M$  be a good orbifold, that is the universal orbifold cover  $\widetilde{M}$  of  $M$  is a smooth manifold. Let  $\widetilde{W} \rightarrow \widetilde{M}$  be a  $\Gamma$ -invariant Hermitian vector bundle over  $\widetilde{M}$ . Let  $D$  be a 1st order elliptic differential operator on  $M$ ,

$$D : L^2(M, \mathcal{E}) \rightarrow L^2(M, \mathcal{F})$$

acting on  $L^2$  orbifold sections of the orbifold vector bundles  $\mathcal{E}, \mathcal{F}$  over  $M$ . By fiat,  $D$  is a  $\Gamma$ -equivariant 1st order elliptic differential operator  $\tilde{D}$  on the smooth manifold  $\widetilde{M}$ ,

$$\tilde{D} : L^2(\widetilde{M}, \tilde{\mathcal{E}}) \rightarrow L^2(\widetilde{M}, \tilde{\mathcal{F}}).$$

Given any connection  $\nabla^{\widetilde{W}}$  on  $\widetilde{W}$  which is compatible with the  $\Gamma$  action and the Hermitian metric, we wish to define an extension of the elliptic operator  $\tilde{D}$ , to act on sections of  $\tilde{\mathcal{E}} \otimes \widetilde{W}, \tilde{\mathcal{F}} \otimes \widetilde{W}$ .

$$\tilde{D} \otimes \nabla^{\widetilde{W}} : \Gamma(M, \tilde{\mathcal{E}} \otimes \widetilde{W}) \rightarrow \Gamma(M, \tilde{\mathcal{F}} \otimes \widetilde{W})$$

and we want it to satisfy the following property: If  $\widetilde{W}$  is a trivial bundle, and  $\nabla^0$  is the trivial connection on  $\widetilde{W}$ , then for  $u \in \Gamma(\widetilde{M}, \tilde{\mathcal{E}})$ ,  $h \in \Gamma(\widetilde{M}, \widetilde{W})$  such that  $\nabla^0 h = 0$ ,

$$(\tilde{D} \otimes \nabla^0)(u \otimes h) = (\tilde{D}u) \otimes h$$

To do this, define a morphism

$$\begin{aligned} S = S_D &: \tilde{\mathcal{E}} \otimes T^*\widetilde{M} \rightarrow \tilde{\mathcal{F}} \\ S(u \otimes df) &= \tilde{D}(fu) - f\tilde{D}u \end{aligned}$$

for  $f \in C^\infty(\widetilde{M})$  and  $u \in \Gamma(M, \tilde{\mathcal{E}})$ . Then  $S$  is a tensorial. Consider  $S = S \otimes 1 : \tilde{\mathcal{E}} \otimes T^*\widetilde{M} \otimes \widetilde{W} \rightarrow \tilde{\mathcal{F}} \otimes \widetilde{W}$  defined by

$$S(u \otimes df \otimes e) = S(u \otimes df) \otimes e$$

for  $u, f$  as before and  $e \in \Gamma(M, \widetilde{W})$ .

Recall that a connection  $\nabla^{\widetilde{W}}$  on  $\widetilde{W}$  is a derivation

$$\nabla^{\widetilde{W}} : \Gamma(\widetilde{M}, \widetilde{W}) \rightarrow \Gamma(\widetilde{M}, T^*\widetilde{M} \otimes \widetilde{W})$$

Define  $\tilde{D} \otimes \nabla^{\widetilde{W}}$  as

$$(\tilde{D} \otimes \nabla^{\widetilde{W}})(u \otimes e) = (Du) \otimes e + S(u \otimes \nabla^{\widetilde{W}}e)$$

Then  $\tilde{D} \otimes \nabla^{\widetilde{W}}$  is a 1<sup>st</sup> order elliptic operator.

### 1.8. Twisted index theorem for orbifolds

Let  $M$  be a compact orbifold of dimension  $n = 4\ell$ . Let  $\Gamma \rightarrow \widetilde{M} \xrightarrow{p} M$  be the universal orbifold cover of  $M$  and the orbifold fundamental group is  $\Gamma$ . Let  $D$  be an elliptic 1st order operator on  $M$ , that is a  $\tilde{D}$  on  $\widetilde{M}$ ,

$$\tilde{D} : L^2(\widetilde{M}, \tilde{\mathcal{E}}) \rightarrow L^2(\widetilde{M}, \tilde{\mathcal{F}}),$$

such that  $\tilde{D}$  commutes with the  $\Gamma$ -action on  $\widetilde{M}$ .

Now let  $\tilde{\omega}$  be a  $\Gamma$ -invariant closed 2-form on  $\widetilde{M}$ ,  $\tilde{\omega} = d\eta$ . Define  $\nabla = d + i\eta$ . Then  $\nabla$  is a Hermitian connection on the trivial line bundle over  $\widetilde{M}$ , and the curvature of  $\nabla$ ,  $(\nabla)^2 = i\tilde{\omega}$ . (Here  $s \in \mathbb{R}$ .) Then  $\nabla$  defines a projective  $(\Gamma, \sigma)$ -action on  $L^2$  spinors as in section 1.2.

Consider the *twisted elliptic operator* on  $\widetilde{M}$ ,

$$\tilde{D} \otimes \nabla : L^2(\widetilde{M}, \tilde{\mathcal{E}}) \rightarrow L^2(\widetilde{M}, \tilde{\mathcal{F}})$$

Then  $\tilde{D} \otimes \nabla$  no longer commutes with  $\Gamma$ , but it does commute with the projective  $(\Gamma, \sigma)$  action. Let  $P_+, P_-$  be the orthogonal projections onto the null space of  $\tilde{D} \otimes \nabla$  and  $(\tilde{D} \otimes \nabla)^*$  respectively since

$$(\tilde{D} \otimes \nabla) P_+ = 0 \quad \text{and} \quad (\tilde{D} \otimes \nabla)^* P_- = 0$$

By elliptic regularity, it follows that the Schwartz (or integral) kernels of  $P_{\pm}$  are smooth. Since  $\tilde{D} \otimes \nabla$  and its adjoint commutes with the  $(\Gamma, \sigma)$  action, one has

$$e^{-i\phi_{\gamma}(x)} P_{\pm}(\gamma x, \gamma y) e^{i\phi_{\gamma}(y)} = P_{\pm}(x, y) \quad \forall \gamma \in \Gamma.$$

In particular,  $P_{\pm}(x, x)$  is smooth and  $\Gamma$ -invariant on  $\widetilde{M}$ . Therefore the corresponding von Neumann trace (cf. section 1.2) is *finite*,

$$\text{tr}(P_{\pm}) = \int_M \underline{\text{tr}}(P_{\pm}(x, x)) dx < \infty.$$

The  $L^2$ -index is by definition

$$\text{index}_{L^2}(\tilde{D} \otimes \nabla) = \text{tr}(P_+) - \text{tr}(P_-).$$

To describe the next theorem, we will briefly review some material on characteristic classes for orbifold vector bundles. Let  $M$  be a good orbifold, that is the universal orbifold cover  $\Gamma \rightarrow \widetilde{M} \rightarrow M$  of  $M$  is a smooth manifold. Then the orbifold tangent bundle  $TM$  of  $M$ , can be viewed as the  $\Gamma$ -equivariant bundle  $T\widetilde{M}$  on  $\widetilde{M}$ . Similar comments apply to the orbifold cotangent bundle  $T^*M$  and more generally, any orbifold vector bundle on  $M$ . It is then clear that choosing  $\Gamma$ -invariant connections on the  $\Gamma$ -invariant vector bundles on  $\widetilde{M}$ , one can define the Chern-Weil representatives of the characteristic classes of the  $\Gamma$ -invariant vector bundles on  $\widetilde{M}$ . These characteristic classes are  $\Gamma$ -invariant and so define cohomology classes on  $M$ . For further details, see <sup>25</sup>.

**Theorem 1.7** *Let  $M$  be a compact, even dimensional, good orbifold,  $\Gamma$  be its orbifold fundamental group,  $\tilde{D}$  be a  $\Gamma$ -invariant twisted Dirac operator on  $\widetilde{M}$ , where  $\Gamma \rightarrow \widetilde{M} \rightarrow M$  is the universal orbifold cover of  $M$ . Then one has*

$$\text{index}_{L^2}(\tilde{D} \otimes \nabla) = \frac{q!}{(2\pi i)^q (2q!)} \langle Td(M) \cup \text{ch}(\text{symb}(D)) \cup e^{\omega}, [T^*M] \rangle$$

where  $Td(M)$  denotes the Todd characteristic class of the complexified orbifold tangent bundle of  $M$  which is pulled back to the orbifold cotangent bundle  $T^*M$ ,  $\text{ch}(\text{symb}(D))$  is the Chern character of the symbol of the operator  $D$ ,

**Proof.**

The proof is similar to the case of Atiyah's  $L^2$  index theorem for covering spaces. An important conceptual difference lies in the fact that  $\widetilde{M}$  is an orbifold cover, and not an actual cover of  $M$ . We have  $\widetilde{D} = \widetilde{\partial}_{\mathcal{E}}^{\pm} \otimes \nabla^{\mathcal{E}} = \widetilde{\partial}_{\mathcal{E}}^{\pm}$ . Let  $k^{\pm}(t, x, y)$  denote the heat kernel of the  $\Gamma$ -invariant Dirac operators  $(\widetilde{\partial}_{\mathcal{E}}^{\pm} \otimes \nabla)^2$  on the universal orbifold cover of  $M$ , and  $P^{\pm}(x, y)$  the smooth Schwartz kernels of the orthogonal projections  $P^{\pm}$  onto the null space of  $\widetilde{\partial}_{\mathcal{E}}^{\pm} \otimes \nabla^s$ . By a general result of Cheeger-Gromov-Taylor<sup>10</sup> (see also<sup>33</sup>), the heat kernel  $k^{\pm}(t, x, y)$  converges uniformly over compact subsets of  $\widetilde{M} \times \widetilde{M}$  to  $P^{\pm}(x, y)$ , as  $t \rightarrow \infty$ . Therefore one has

$$\begin{aligned} \lim_{t \rightarrow \infty} \text{tr}(e^{-t(\widetilde{\partial}_{\mathcal{E}}^{\pm} \otimes \nabla)^2}) &= \lim_{t \rightarrow \infty} \int_M \underline{\text{tr}}(k^{\pm}(t, x, x)) dx \\ &= \int_M \underline{\text{tr}}(P^{\pm}(x, x)) dx \\ &= \text{tr}(P^{\pm}) \end{aligned} \quad (1.3)$$

Next observe that

$$\begin{aligned} \frac{\partial}{\partial t} \text{tr}_s(e^{-t(\widetilde{\partial}_{\mathcal{E}} \otimes \nabla)^2}) &= -\text{tr}_s((\widetilde{\partial}_{\mathcal{E}} \otimes \nabla)^2 e^{-t(\widetilde{\partial}_{\mathcal{E}} \otimes \nabla)^2}) \\ &= -\text{tr}_s([\widetilde{\partial}_{\mathcal{E}} \otimes \nabla, (\widetilde{\partial}_{\mathcal{E}} \otimes \nabla)e^{-t(\widetilde{\partial}_{\mathcal{E}} \otimes \nabla)^2}]) \\ &= 0 \end{aligned}$$

since  $\widetilde{\partial}_{\mathcal{E}} \otimes \nabla$  is an odd operator. Here  $\text{tr}_s$  denotes the graded trace, i.e. the composition of the trace  $\text{tr}$  and the grading operator. Therefore we deduce that

$$\begin{aligned} \text{tr}_s(e^{-t(\widetilde{\partial}_{\mathcal{E}} \otimes \nabla)^2}) &= \lim_{t \rightarrow \infty} \text{tr}_s(e^{-t(\widetilde{\partial}_{\mathcal{E}} \otimes \nabla)^2}) \\ &= \text{tr}_s(P) \\ &= \text{index}_{L^2}(\widetilde{\partial}_{\mathcal{E}}^+ \otimes \nabla). \end{aligned} \quad (1.4)$$

By the local index theorem of Atiyah-Bott-Patodi<sup>2</sup>, Getzler<sup>17</sup>, one has

$$\lim_{t \rightarrow 0} (\underline{\text{tr}}(k^+(t, x, x)) - \underline{\text{tr}}(k^-(t, x, x))) = [\widehat{A}(\Omega) \text{tr}(e^{R^{\widetilde{\mathcal{E}}}}) e^{\omega}]_n \quad (1.5)$$

where  $[ ]_n$  denotes the component of degree  $n = \dim M$ ,  $\Omega$  is the curvature of the metric on  $\widetilde{M}$ ,  $R^{\widetilde{\mathcal{E}}}$  is the curvature of the connection on  $\widetilde{\mathcal{E}}$ . Combining equations (1.3), (1.4) and (1.5), one has

$$\text{index}_{L^2}(\widetilde{\partial}_{\mathcal{E}}^+ \otimes \nabla) = \int_M \widehat{A}(\Omega) \text{tr}(e^{R^{\widetilde{\mathcal{E}}}}) e^{\omega}.$$

◊

**Remarks 1.8** A particular case of Theorem 1.7 highlights a key new phenomenon in the case of orbifolds, viz. in the special case when the multiplier  $\sigma = 1$  is trivial, then the

$\text{index}_{L^2}(\tilde{D})$  formally coincides the  $L^2$  index of  $\tilde{D}$  as defined Atiyah<sup>1</sup>. By comparing with the cohomological formula due to Kawasaki<sup>25</sup> for the Fredholm index of the operator  $D$  on the orbifold  $M$ , we see that in general these are *not* equal, and the error term is a rational number which can be expressed explicitly as a cohomological formula on the lower dimensional strata of the orbifold  $M$ . Thus, we see that for general orbifolds the  $L^2$  index of  $\tilde{D}$  is only a *rational* number. This was also observed by<sup>15</sup>. This is in contrast to the situation when the orbifold is smooth, where Atiyah's  $L^2$  index theorem establishes the integrality of the  $L^2$  index in this case.

## 2. Range of the trace and the Kadison constant

In this section, we will first calculate the range of the canonical trace map on  $K_0$  of the twisted group  $C^*$ -algebras for Fuchsian groups  $\Gamma$  of signature  $(g, \nu_1, \dots, \nu_n)$ . We use in an essential way some of the results of the previous section such as the twisted version of the  $L^2$ -index theorem of Atiyah<sup>1</sup>, which is due to Gromov<sup>20</sup>, and which is proved in Theorem 1.7. This enables us to deduce information about projections in the twisted group  $C^*$ -algebras. In the case of no twisting, this follows because the Baum-Connes conjecture is known to be true while these results are also well known for the case of the irrational rotation algebras, and for the twisted groups  $C^*$  algebras of the fundamental groups of closed Riemann surfaces of positive genus<sup>9</sup>. Our theorem generalizes most of these results. Moreover, we prove analogous results in the case of compact, real and complex hyperbolic four-manifolds. We will apply the results of this section in the next section to study some quantitative aspects of the spectrum of projectively periodic elliptic operators, mainly on orbifold covering spaces of hyperbolic orbifolds.

### 2.1. The isomorphism classes of algebras $C^*(\Gamma, \sigma)$

Let  $\sigma \in Z^2(\Gamma, \mathbf{U}(1))$  be a multiplier on  $\Gamma$ , where  $\Gamma$  is a Fuchsian group of signature  $(g, \nu_1, \dots, \nu_n)$ . If  $\sigma' \in Z^2(\Gamma, \mathbf{U}(1))$  is another multiplier on  $\Gamma$  such that  $[\sigma] = [\sigma'] \in H^2(\Gamma, \mathbf{U}(1))$ , then it can be easily shown that  $C^*(\Gamma, \sigma) \cong C^*(\Gamma, \sigma')$ . That is, the isomorphism classes of the  $C^*$ -algebras  $C^*(\Gamma_{g'}, \sigma)$  are naturally parameterized by  $H^2(\Gamma, \mathbf{U}(1))$ . In particular, if we consider only multipliers  $\sigma$  such that  $\delta(\sigma) = 0$ , we see that these are parameterized by  $\ker(\delta) \subset H^2(\Gamma, \mathbf{U}(1))$ . It follows from the discussion at the beginning of the next subsection that  $\ker(\delta) \cong \mathbf{U}(1)$ . We summarize this below.

**Lemma 2.9** *Let  $\Gamma$  be a Fuchsian group of signature  $(g, \nu_1, \dots, \nu_n)$ . Then the isomorphism classes of twisted group  $C^*$ -algebras  $C^*(\Gamma, \sigma)$  such that  $\delta(\sigma) = 0$  are naturally parameterized by  $\mathbf{U}(1)$ .*

### 2.2. K-theory of twisted group $C^*$ algebras

We begin by computing the  $K$ -theory of twisted group  $C^*$ -algebras for Fuchsian groups  $\Gamma$  of signature  $(g, \nu_1, \dots, \nu_n)$ . Let  $\sigma$  be a multiplier on  $\Gamma$ . It defines a cohomology class  $[\sigma] \in H^2(\Gamma, \mathbf{U}(1))$ . Consider now the short exact sequence of coefficient groups

$$1 \rightarrow \mathbb{Z} \xrightarrow{i} \mathbb{R} \xrightarrow{e^{2\pi\sqrt{-1}}} \mathbf{U}(1) \rightarrow 1,$$

which gives rise to a long exact sequence of cohomology groups (the change of coefficient groups sequence)

$$\dots \rightarrow H^2(\Gamma, \mathbb{Z}) \xrightarrow{i_*} H^2(\Gamma, \mathbb{R}) \xrightarrow{e^{2\pi\sqrt{-1}} *} H^2(\Gamma, \mathbf{U}(1)) \xrightarrow{\delta} H^3(\Gamma, \mathbb{Z}) \xrightarrow{i_*} H^3(\Gamma, \mathbb{R}). \quad (2.6)$$

We first show that the map

$$H^2(\Gamma, \mathbf{U}(1)) \xrightarrow{\delta} H^3(\Gamma, \mathbb{Z})$$

is a surjection.

In fact, it is enough to show that  $H^3(\Gamma, \mathbb{R}) = \{0\}$ . In order to see this it is enough to notice that we have a  $G$  action on  $B\Gamma_{g'}$  with quotient  $B\Gamma$ ,

$$G \rightarrow B\Gamma_{g'} \xrightarrow{\lambda} B\Gamma \quad (2.7)$$

and therefore, in the Leray-Serre spectral sequence, we have

$$E^2 = \text{Tor}^{H_*(G, \mathbb{R})}(\mathbb{R}, H_*(B\Gamma_{g'}, \mathbb{R}))$$

that converges to  $H_*(B\Gamma, \mathbb{R})$ . Moreover, we have

$$E^2 = \text{Tor}^{H_*(G, \mathbb{R})}(\mathbb{R}, \mathbb{R})$$

converging to  $H_*(BG, \mathbb{R})$ , see 7.16 of <sup>29</sup>.

Notice also that, with  $\mathbb{R}$  coefficients, we have  $H_q(BG, \mathbb{R}) = \{0\}$  for  $q > 0$ . Thus we obtain that, with  $\mathbb{R}$  coefficients,  $H_q(B\Gamma, \mathbb{R}) \cong H^q(B\Gamma, \mathbb{R})$  is  $\mathbb{R}$  in degrees  $q = 0$  and  $q = 2$ ,  $\mathbb{R}^{2g}$  in degree  $q = 1$ , and trivial in degrees  $q > 2$ . In particular, (2.6) now becomes

$$\dots \rightarrow H^2(\Gamma, \mathbb{Z}) \xrightarrow{i_*} H^2(\Gamma, \mathbb{R}) \xrightarrow{e^{2\pi\sqrt{-1}} *} H^2(\Gamma, \mathbf{U}(1)) \xrightarrow{\delta} H^3(\Gamma, \mathbb{Z}) \xrightarrow{i_*} 0. \quad (2.8)$$

In the following  $[\Gamma]$  will denote a choice of a generator in

$$H_2(B\Gamma, \mathbb{R}) \cong \mathbb{R} \cong H^2(B\Gamma, \mathbb{R}).$$

Using equation (2.7) and the previous argument, we see that  $\lambda_*[\Sigma_{g'}] = \#(G)[\Gamma]$ , since  $B\Gamma_{g'}$  and  $\Sigma_{g'}$  are homotopy equivalent, and where  $\#(G)$  denotes the order of the finite group  $G$ .

In particular, for any multiplier  $\sigma$  of  $\Gamma$  with  $[\sigma] \in H^2(\Gamma_{g'}, \mathbf{U}(1))$  and with  $\delta(\sigma) = 0$ , there is a  $\mathbb{R}$ -valued 2-cocycle  $\zeta$  on  $\Gamma$  with  $[\zeta] \in H^2(\Gamma, \mathbb{R})$  such that  $[e^{2\pi\sqrt{-1}\zeta}] = [\sigma]$ . Define a homotopy  $[\sigma_t] = [e^{2\pi\sqrt{-1}t\zeta}] \quad \forall t \in [0, 1]$  which is a homotopy of multipliers  $\sigma_t$  that connects the multiplier  $\sigma$  and the trivial multiplier. Note also that this homotopy is *canonical* and not dependent on the particular choice of  $\zeta$ . Therefore one obtains a homotopy of isomorphism classes of twisted group  $C^*$ -algebras  $C^*(\Gamma, \sigma_t)$  connecting  $C^*(\Gamma, \sigma)$  and  $C^*(\Gamma)$ . It is this homotopy which will essentially be used to show that  $C^*(\Gamma, \sigma)$  and  $C^*(\Gamma)$  have the same  $K$ -theory.

Let  $\Gamma \subset G$  be a discrete cocompact subgroup of  $G$  and  $A$  be an algebra admitting an action of  $\Gamma$  by automorphisms. Then the cross product algebra  $[A \otimes C_0(G)] \rtimes \Gamma$ , is Morita equivalent to the algebra of continuous sections vanishing at infinity  $C_0(\Gamma \backslash G, \mathcal{E})$ , where  $\mathcal{E} \rightarrow \Gamma \backslash G$  is the flat  $A$ -bundle defined as the quotient

$$\mathcal{E} = (A \times G)/\Gamma \rightarrow \Gamma \backslash G. \quad (2.9)$$

Here we consider the diagonal action of  $\Gamma$  on  $A \times G$ . We refer the reader to <sup>23</sup> for the technical definition of a  $K$ -amenable group. However we mention that any solvable Lie group, and in fact any amenable Lie group is  $K$ -amenable, and in fact it is shown in <sup>23</sup>, <sup>22</sup> that the non-amenable groups  $\mathbf{SO}_0(n, 1)$ ,  $\mathbf{SU}(n, 1)$  are  $K$ -amenable Lie groups. Also, Cuntz <sup>13</sup> has shown that the class of  $K$ -amenable groups is closed under the operations of taking subgroups, under free products and under direct products.

**Theorem 2.10** (<sup>23, 24</sup>) *If  $G$  is  $K$ -amenable, then  $(A \rtimes \Gamma) \otimes C_0(G)$  and  $[A \otimes C_0(G)] \rtimes \Gamma$  have the same  $K$ -equivariant  $K$ -theory, where  $K$  acts in the standard way on  $G$  and trivially on the other factors.*

Combining Theorem 2.10 with the remarks above, one gets the following important corollary.

**Corollary 2.11** *If  $G$  is  $K$ -amenable, then  $(A \rtimes \Gamma) \otimes C_0(G)$  and  $C_0(\Gamma \backslash G, \mathcal{E})$  have the same  $K$ -equivariant  $K$ -theory. Equivalently, one has for  $j = 0, 1$ ,*

$$K_{Kj}(C_0(\Gamma \backslash G, \mathcal{E})) \cong K_{Kj+\dim(G/K)}(A \rtimes \Gamma).$$

We now come to the main theorem of this section, which generalizes theorems of <sup>9, 31</sup>, <sup>32</sup>.

**Theorem 2.12** *Suppose given  $\Gamma$  a discrete cocompact subgroup in a  $K$ -amenable Lie group  $G$  and suppose that  $K$  is a maximal compact subgroup of  $G$ . Then*

$$K_{\bullet}(C^*(\Gamma, \sigma)) \cong K_{K}^{\bullet+\dim(G/K)}(\Gamma \backslash G, \delta(B_{\sigma})),$$

where  $\sigma \in H^2(\Gamma, \mathbf{U}(1))$  is any multiplier on  $\Gamma$ . Here  $K_{K}^{\bullet}(\Gamma \backslash G, \delta(B_{\sigma}))$  is the twisted  $K$ -equivariant  $K$ -theory of a continuous trace  $C^*$ -algebra  $B_{\sigma}$  with spectrum  $\Gamma \backslash G$ , and  $\delta(B_{\sigma})$  denotes the Dixmier-Douady invariant of  $B_{\sigma}$ .

**Proof.** Let  $\sigma \in H^2(\Gamma, \mathbf{U}(1))$ , then the *twisted* cross product algebra  $A \rtimes_\sigma \Gamma$  is stably equivalent to the cross product  $(A \otimes \mathcal{K}) \rtimes \Gamma$  where  $\mathcal{K}$  denotes compact operators. This is the Packer-Raeburn stabilization trick<sup>31</sup>, which we now describe in more detail. Let  $V : \Gamma \rightarrow U(\ell^2(\Gamma))$  denote the left regular  $(\Gamma, \bar{\sigma})$  representation on  $\ell^2(\Gamma)$ , i.e. for  $\gamma, \gamma_1 \in \Gamma$  and  $f \in \ell^2(\Gamma)$

$$(V(\gamma_1)f)(\gamma) = \bar{\sigma}(\gamma_1, \gamma_1^{-1}\gamma)f(\gamma_1^{-1}\gamma).$$

Then for  $\gamma_1, \gamma_2 \in \ell^2(\Gamma)$ ,  $V$  satisfies  $V(\gamma_1)V(\gamma_2) = \bar{\sigma}(\gamma_1, \gamma_2)V(\gamma_1\gamma_2)$ . That is,  $V$  is a projective representation of  $\Gamma$ . Since  $Ad$  is trivial on  $\mathbf{U}(1)$ , it follows that  $\alpha(\gamma) = Ad(V(\gamma))$  is a representation of  $\Gamma$  on  $\mathcal{K}$ . This is easily generalized to the case when  $\mathbb{C}$  is replaced by the  $*$  algebra  $A$ .

Using Corollary 2.11, one sees that  $A \rtimes_\sigma \Gamma \otimes C_0(G)$  and  $C_0(\Gamma \backslash G, \mathcal{E}_\sigma)$  have the same  $K$ -equivariant  $K$ -theory, whenever  $G$  is  $K$ -amenable, where

$$\mathcal{E}_\sigma = (A \otimes \mathcal{K} \times G)/\Gamma \rightarrow \Gamma \backslash G$$

is a flat  $A \otimes \mathcal{K}$ -bundle over  $\Gamma \backslash G$  and  $K$  is a maximal compact subgroup of  $G$ . In the particular case when  $A = \mathbb{C}$ , one sees that  $C_r^*(\Gamma, \sigma) \otimes C_0(G)$  and  $C_0(\Gamma \backslash G, \mathcal{E}_\sigma)$  have the same  $K$ -equivariant  $K$ -theory whenever  $G$  is  $K$ -amenable, where

$$\mathcal{E}_\sigma = (\mathcal{K} \times G)/\Gamma \rightarrow \Gamma \backslash G.$$

But the twisted  $K$ -equivariant  $K$ -theory  $K_K^*(\Gamma \backslash G, \delta(B_\sigma))$  is by definition the same as the  $K$ -equivariant  $K$ -theory of the continuous trace  $C^*$ -algebra  $B_\sigma = C_0(\Gamma \backslash G, \mathcal{E}_\sigma)$  with spectrum  $\Gamma \backslash G$ . Therefore

$$K_\bullet(C^*(\Gamma, \sigma)) \cong K_K^{\bullet + \dim(G/K)}(\Gamma \backslash G, \delta(B_\sigma)).$$

◇

Our next main result says that for discrete cocompact subgroups in  $K$ -amenable Lie groups, the reduced and unreduced twisted group  $C^*$ -algebras have canonically isomorphic  $K$ -theories. Therefore all the results that we prove regarding the  $K$ -theory of these reduced twisted group  $C^*$ -algebras are also valid for the unreduced twisted group  $C^*$ -algebras.

**Theorem 2.13** *Let  $\sigma \in H^2(\Gamma, \mathbf{U}(1))$  be a multiplier on  $\Gamma$  and  $\Gamma$  be a discrete cocompact subgroup in a  $K$ -amenable Lie group. Then the canonical morphism  $C^*(\Gamma, \sigma) \rightarrow C_r^*(\Gamma, \sigma)$  induces an isomorphism*

$$K_*(C^*(\Gamma, \sigma)) \cong K_*(C_r^*(\Gamma, \sigma)).$$

**Proof.** We note that by the Packer-Raeburn trick, one has

$$C^*(\Gamma, \sigma) \otimes \mathcal{K} \cong \mathcal{K} \rtimes \Gamma$$

and

$$C_r^*(\Gamma, \sigma) \otimes \mathcal{K} \cong \mathcal{K} \rtimes_r \Gamma,$$

where  $\rtimes_r$  denotes the reduced crossed product. Since  $\Gamma$  is a lattice in a  $K$ -amenable Lie group, the canonical morphism  $\mathcal{K} \rtimes \Gamma \rightarrow \mathcal{K} \rtimes_r \Gamma$  induces an isomorphism (cf. <sup>13</sup>)

$$K_*(\mathcal{K} \rtimes \Gamma) \cong K_*(\mathcal{K} \rtimes_r \Gamma),$$

which proves the result.  $\diamond$

We now specialize to the case where we have  $G = \mathbf{SO}_0(2, 1)$ ,  $K = \mathbf{SO}(2)$  and  $\Gamma = \Gamma(g, \nu_1, \dots, \nu_n)$  is a Fuchsian group, i.e. the orbifold fundamental group of a hyperbolic orbifold of signature  $(g, \nu_1, \dots, \nu_n)$ ,  $\Sigma(g, \nu_1, \dots, \nu_n)$ , where  $\Gamma \subset G$  (note that  $G$  is  $K$ -amenable), or when  $G = \mathbb{R}^2$ ,  $K = \{e\}$  and  $g = 1$ , with  $\Gamma$  being a cocompact crystallographic group.

**Proposition 2.14** *Let  $\sigma$  be a multiplier on the Fuchsian group  $\Gamma$  of signature  $(g, \nu_1, \dots, \nu_n)$  such that  $\delta(\sigma) = 0$ . Then one has*

1.  $K_0(C^*(\Gamma, \sigma)) \cong K_0(C^*(\Gamma)) \cong K_{orb}^0(\Sigma(g, \nu_1, \dots, \nu_n)) \cong \mathbb{Z}^{2-n+\sum_{j=1}^n \nu_j}$
2.  $K_1(C^*(\Gamma, \sigma)) \cong K_1(C^*(\Gamma)) \cong K_{orb}^1(\Sigma(g, \nu_1, \dots, \nu_n)) \cong \mathbb{Z}^{2g}.$

**Proof.** Now by a result due to Kasparov <sup>23</sup>, which he proves by connecting the regular representation to the trivial one via the complementary series, one has

$$K_\bullet(C^*(\Gamma)) \cong K_{\mathbf{SO}(2)}^\bullet(P(g, \nu_1, \dots, \nu_n)) = K_{orb}^\bullet(\Sigma(g, \nu_1, \dots, \nu_n)).$$

We recall next the calculation of Farsi <sup>15</sup> for the orbifold  $K$ -theory of the hyperbolic orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$

$$\begin{aligned} K_{orb}^0(\Sigma(g, \nu_1, \dots, \nu_n)) &\equiv K_0(C^*(\Sigma(g, \nu_1, \dots, \nu_n))) \\ &= K_{\mathbf{SO}(2)}^0(P(g, \nu_1, \dots, \nu_n)) \cong \mathbb{Z}^{2-n+\sum_{j=1}^n \nu_j} \end{aligned}$$

and

$$\begin{aligned} K_{orb}^1(\Sigma(g, \nu_1, \dots, \nu_n)) &\equiv K_1(C^*(\Sigma(g, \nu_1, \dots, \nu_n))) \\ &= K_{\mathbf{SO}(2)}^1(P(g, \nu_1, \dots, \nu_n)) \cong \mathbb{Z}^{2g} \end{aligned}$$

By Theorem 2.12 we have

$$K_j(C^*(\Gamma)) \cong K_{\mathbf{SO}(2)}^j(P(g, \nu_1, \dots, \nu_n)) \quad \text{for } j = 0, 1,$$

and more generally

$$K_j(C^*(\Gamma, \sigma)) \cong K_{\mathbf{SO}(2)}^j(P(g, \nu_1, \dots, \nu_n), \delta(B_\sigma)), \quad j = 0, 1,$$

where  $B_\sigma = C(P(g, \nu_1, \dots, \nu_n), \mathcal{E}_\sigma)$ . Finally, because  $\mathcal{E}_\sigma$  is a locally trivial bundle of  $C^*$ -algebras over  $P(g, \nu_1, \dots, \nu_n)$ , with fiber  $\mathcal{K}$  (= compact operators), it has a Dixmier-Douady invariant  $\delta(B_\sigma)$  which can be viewed as the obstruction to  $B_\sigma$  being Morita equivalent to  $C(\Sigma_g)$ . But by assumption  $\delta(B_\sigma) = \delta(\sigma) = 0$ . Therefore  $B_\sigma$  is Morita equivalent to  $C(P(g, \nu_1, \dots, \nu_n))$  and we conclude that

$$K_j(C^*(\Gamma, \sigma)) \cong K_{\text{SO}(2)}^j(P(g, \nu_1, \dots, \nu_n)) \cong K_{\text{orb}}^j(\Sigma(g, \nu_1, \dots, \nu_n)) \quad j = 0, 1.$$

◇

### 2.3. Twisted Kasparov map

Let  $\Gamma$  be as before, that is,  $\Gamma$  is the orbifold fundamental group of the hyperbolic orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$ . Then for any multiplier  $\sigma$  on  $\Gamma$ , the *twisted Kasparov isomorphism*,

$$\mu_\sigma : K_{\text{orb}}^\bullet(\Sigma(g, \nu_1, \dots, \nu_n)) \rightarrow K_\bullet(C_r^*(\Gamma, \sigma)) \quad (2.10)$$

is defined as follows. Let

$$\mathcal{E} \rightarrow \Sigma(g, \nu_1, \dots, \nu_n)$$

be an orbifold vector bundle over  $\Sigma(g, \nu_1, \dots, \nu_n)$  defining an element

$$[\mathcal{E}] \in K^0(\Sigma(g, \nu_1, \dots, \nu_n)).$$

As in <sup>25</sup>, one can form the twisted Dirac operator

$$\partial_\mathcal{E}^+ : L^2(\Sigma(g, \nu_1, \dots, \nu_n), \mathcal{S}^+ \otimes \mathcal{E}) \rightarrow L^2(\Sigma(g, \nu_1, \dots, \nu_n), \mathcal{S}^- \otimes \mathcal{E})$$

where  $\mathcal{S}^\pm$  denote the  $\frac{1}{2}$  spinor bundles over  $\Sigma(g, \nu_1, \dots, \nu_n)$ . By Proposition 2.14 of the previous subsection, there is a canonical isomorphism

$$K_\bullet(C_r^*(\Gamma, \sigma)) \cong K_{\text{orb}}^\bullet(\Sigma(g, \nu_1, \dots, \nu_n)).$$

Both of these maps are assembled to yield the twisted Kasparov map as in (2.10). Observe that  $\Sigma(g, \nu_1, \dots, \nu_n) = \underline{B}\Gamma$ , and that the twisted Kasparov map has a natural generalization, which will be studied elsewhere.

We next describe this map more explicitly. One can lift the twisted Dirac operator  $\partial_\mathcal{E}^+$  as above, to a  $\Gamma$ -invariant operator  $\widetilde{\partial}_\mathcal{E}^+$  on  $\mathbf{H} = \widetilde{\Sigma}(g, \nu_1, \dots, \nu_n)$ , which is the universal orbifold cover of  $\Sigma(g, \nu_1, \dots, \nu_n)$ ,

$$\widetilde{\partial}_\mathcal{E}^+ : L^2(\mathbf{H}, \widetilde{\mathcal{S}^+ \otimes \mathcal{E}}) \rightarrow L^2(\mathbf{H}, \widetilde{\mathcal{S}^- \otimes \mathcal{E}})$$

Therefore as before in (2.8), for any multiplier  $\sigma$  of  $\Gamma$  with  $\delta([\sigma]) = 1$ , there is a  $\mathbb{R}$ -valued 2-cocycle  $\zeta$  on  $\Gamma$  with  $[\zeta] \in H^2(\Gamma, \mathbb{R})$  such that  $[e^{2\pi\sqrt{-1}\zeta}] = [\sigma]$ . By the earlier argument using spectral sequences and the fibration as in equation (2.7), we see that the

map  $\lambda$  induces an isomorphism  $H^2(\Gamma, \mathbb{R}) \cong H^2(\Gamma_{g'}, \mathbb{R})$ , and therefore there is a 2-form  $\omega$  on  $\Sigma_{g'}$  such that  $[e^{2\pi\sqrt{-1}\omega}] = [\sigma]$ . Of course, the choice of  $\omega$  is not unique, but this will not affect the results that we are concerned with. Let  $\tilde{\omega}$  denote the lift of  $\omega$  to the universal cover  $\mathbf{H}$ . Since the hyperbolic plane  $\mathbf{H}$  is contractible, it follows that  $\tilde{\omega} = d\eta$  where  $\eta$  is a 1-form on  $\mathbf{H}$  which is not in general  $\Gamma$  invariant. Now  $\nabla = d - i\eta$  is a Hermitian connection on the trivial complex line bundle on  $\mathbf{H}$ . Note that the curvature of  $\nabla$  is  $\nabla^2 = i\tilde{\omega}$ . Consider now the twisted Dirac operator  $\widetilde{\partial}_{\mathcal{E}}^+$  which is twisted again by the connection  $\nabla$ ,

$$\widetilde{\partial}_{\mathcal{E}}^+ \otimes \nabla : L^2(\mathbf{H}, \widetilde{\mathcal{S}^+ \otimes \mathcal{E}}) \rightarrow L^2(\mathbf{H}, \widetilde{\mathcal{S}^- \otimes \mathcal{E}}).$$

It does not commute with the  $\Gamma$  action, but it does commute with the projective  $(\Gamma, \sigma)$ -action which is defined by the multiplier  $\sigma$ , and it has an  $(\Gamma, \sigma)$ - $L^2$ -index

$$\text{ind}_{(\Gamma, \sigma)}(\widetilde{\partial}_{\mathcal{E}}^+ \otimes \nabla) \in K_0(C_r^*(\Gamma, \sigma)).$$

Formally,  $\text{ind}_{(\Gamma, \sigma)}(\widetilde{\partial}_{\mathcal{E}}^+ \otimes \nabla) = [P^+] - [P^-]$ , where  $P^\pm$  denotes the projection to the  $L^2$  kernel of  $\widetilde{\partial}_{\mathcal{E}}^\pm \otimes \nabla$ . The problem is that in general,  $P^\pm$  only lies in the twisted von Neumann algebra, and therefore one has to add a compact perturbation in  $C_r^*(\Gamma, \sigma)$  to the operator, in order to properly define the index. This is essentially the  $C^*$  index of Mishchenko-Fomenko<sup>30</sup>, see also<sup>34</sup>. Then observe that the *twisted Kasparov map* is

$$\mu_\sigma([\mathcal{E}]) = \text{ind}_{(\Gamma, \sigma)}(\widetilde{\partial}_{\mathcal{E}}^+ \otimes \nabla) \in K_0(C^*(\Gamma, \sigma)).$$

The canonical trace on  $C_r^*(\Gamma, \sigma)$ ) induces a linear map

$$[tr] : K_0(C_r^*(\Gamma, \sigma)) \rightarrow \mathbb{R}$$

which is called the *trace map* in  $K$ -theory. Explicitly, we first extend  $tr$  to matrices with entries in  $C^*(\Gamma, \sigma)$  as (with  $\text{Trace}$  denoting matrix trace):  $tr(f \otimes r) = \text{Trace}(r)tr(f)$ . Then the extension of  $tr$  to  $K_0$  is given by  $[tr]([e] - [f]) = tr(e) - tr(f)$ , where  $e, f$  are idempotent matrices with entries in  $C^*(\Gamma, \sigma)$ .

Clearly one has

$$\text{index}_{L^2}(\widetilde{\partial}_{\mathcal{E}}^+ \otimes \nabla) = [tr](\text{ind}_{(\Gamma, \sigma)}(\widetilde{\partial}_{\mathcal{E}}^+ \otimes \nabla))$$

#### 2.4. Range of the trace map on $K_0$ : the case of two dimensional orbifolds

We can now state the first major theorem of this section.

**Theorem 2.15** *Let  $\Gamma$  be a Fuchsian group of signature  $(g, \nu_1, \dots, \nu_n)$ , and  $\sigma$  be a multiplier of  $\Gamma$  such that  $\delta(\sigma) = 0$ . Then the range of the trace map is*

$$[\text{tr}](K_0(C_r^*(\Gamma, \sigma))) = \mathbb{Z}\theta + \mathbb{Z} + \sum_{i=1}^n \mathbb{Z}(1/\nu_i),$$

where  $2\pi\theta = \langle [\sigma], [\Gamma] \rangle \in (0, 1]$  is the result of pairing the multiplier  $\sigma$  with the fundamental class of  $\Gamma$  (cf. subsection 2.1).

### Proof.

We first observe that by the results of the previous subsection the twisted Kasparov map is an isomorphism. Therefore to compute the range of the trace map on  $K_0$ , it suffices to compute the range of the trace map on elements of the form

$$\mu_\sigma([\mathcal{E}^0] - [\mathcal{E}^1])$$

for any element

$$[\mathcal{E}^0] - [\mathcal{E}^1] \in K_{orb}^0(\Sigma(g, \nu_1, \dots, \nu_n)).$$

where  $\mathcal{E}^0, \mathcal{E}^1$  are orbifold vector bundles over the orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$ , which as in section 1.4, can be viewed as  $G$ -equivariant vector bundles over the Riemann surface  $\Sigma_{g'}$  which is an orbifold  $G$  covering of the orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$ .

By the twisted  $L^2$  index theorem for orbifolds, Theorem 1.7, one has

$$[tr](\text{ind}_{(\Gamma, \sigma)}(\widetilde{\partial}_{\mathcal{E}}^+ \otimes \nabla)) = \frac{1}{2\pi} \int_{\Sigma(g, \nu_1, \dots, \nu_n)} \widehat{A}(\Omega) tr(e^{R^{\mathcal{E}}}) e^\omega. \quad (2.11)$$

We next simplify the right hand side of equation (2.11) using

$$\begin{aligned} \widehat{A}(\Omega) &= 1 \\ tr(e^{R^{\mathcal{E}}}) &= \text{rank } \mathcal{E} + tr(R^{\mathcal{E}}) \\ e^\omega &= 1 + \omega. \end{aligned}$$

Therefore one has

$$[tr](\text{ind}_{(\Gamma, \sigma)}(\widetilde{\partial}_{\mathcal{E}}^+ \otimes \nabla)) = \frac{\text{rank } \mathcal{E}}{2\pi} \int_{\Sigma(g, \nu_1, \dots, \nu_n)} \omega + \frac{1}{2\pi} \int_{\Sigma(g, \nu_1, \dots, \nu_n)} tr(R^{\mathcal{E}}),$$

Now by the index theorem for orbifolds, due to Kawasaki <sup>25</sup>, we see that

$$\frac{1}{2\pi} \int_{\Sigma(g, \nu_1, \dots, \nu_n)} tr(R^{\mathcal{E}}) + \frac{1}{2\pi} \sum_{i=1}^n \beta_i / \nu_i = \text{index}(\partial_{\mathcal{E}}^+) \in \mathbb{Z},$$

Therefore we see that

$$\frac{1}{2\pi} \int_{\Sigma(g, \nu_1, \dots, \nu_n)} tr(R^{\mathcal{E}}) \in \mathbb{Z} + \sum_{i=1}^n \mathbb{Z}(1/\nu_i)$$

Observe that

$$\int_{\Sigma(g, \nu_1, \dots, \nu_n)} \omega = \frac{1}{\#(G)} \int_{\Sigma_{g'}} \omega = \langle [\omega], [\Gamma] \rangle$$

since  $\Sigma_{g'}$  is an orbifold  $G$  covering of the orbifold  $\Sigma(g, \nu_1, \dots, \nu_n)$  and  $[\Gamma]$  is equal to  $\frac{[\Sigma_{g'}]}{\#(G)}$ , cf. section 2.1 and that by assumption,

$$\frac{\langle [\omega], [\Gamma] \rangle}{2\pi} - \theta \in \mathbb{Z}.$$

It follows that the range of the trace map on  $K_0$  is

$$\mathbb{Z} \frac{\langle [\omega], [\Gamma] \rangle}{2\pi} + \mathbb{Z} + \sum_{i=1}^n \mathbb{Z}(1/\nu_i) = \mathbb{Z}\theta + \mathbb{Z} + \sum_{i=1}^n \mathbb{Z}(1/\nu_i).$$

◇

We will now discuss one application of this result, leaving further applications to the next section. The application studies the number of projections in the twisted group  $C^*$ -algebra, which is a problem of independent interest.

We first recall the definition of the Kadison constant of a twisted group  $C^*$ -algebra. The *Kadison constant* of  $C_r^*(\Gamma, \sigma)$  is defined by:

$$C_\sigma(\Gamma) = \inf\{tr(P) : P \text{ is a non-zero projection in } C_r^*(\Gamma, \sigma) \otimes \mathcal{K}\}.$$

**Proposition 2.16** *Let  $\Gamma$  be as in Theorem 2.15. Let  $\sigma$  be a multiplier on  $\Gamma$  such that  $\delta(\sigma) = 0$ , and  $2\pi\theta = \langle [\sigma], [\Gamma] \rangle \in (0, 1]$  be the result of pairing the cohomology class of  $\sigma$  with the fundamental class of  $\Gamma$ . If  $\theta$  is rational, then there are at most a finite number of unitary equivalence classes of projections, other than 0 and 1, in the reduced twisted group  $C^*$ -algebra  $C_r^*(\Gamma, \sigma)$ .*

**Proof.** By assumption,  $\theta = p/q$ . Let  $P$  be a projection in  $C_r^*(\Gamma, \sigma)$ . Then  $1 - P$  is also a projection in  $C_r^*(\Gamma, \sigma)$  and one has

$$1 = tr(1) = tr(P) + tr(1 - P).$$

Each term in the above equation is non-negative. Since  $\sigma$  is rational and by Theorem 2.15, it follows that the Kadison constant  $C_\sigma(\Gamma) > 0$  and  $tr(P) \in \{0, C_\sigma(\Gamma), 2C_\sigma(\Gamma), \dots, 1\}$ . By faithfulness and normality of the trace  $tr$ , it follows that there are at most a finite number of unitary equivalence classes of projections, other than those of 0 and 1 in  $C_r^*(\Gamma, \sigma)$ . ◇

## 2.5. Range of the trace map on $K_0$ : the case of 4 dimensional real and complex hyperbolic manifolds

We prove here the analogue of the results of the previous subsection, for the case of compact, real and complex hyperbolic four dimensional manifolds.

We now set some notation for the theorem below. Let  $\Gamma$  be a discrete, torsion-free cocompact subgroup of  $G = \mathbf{SO}_0(1, 4)$  or  $\mathbf{SU}(1, 2)$ . We will assume that  $\delta(\sigma) = 0$ ,

therefore there is a closed  $\Gamma$ -invariant two form  $\omega$  on  $G/K$ , where  $K$  is a maximal compact subgroup of  $G$ , such that  $[e^{2i\pi\omega}] = [\sigma]$ . Let  $Q(a, b) = \langle a \cup b, [\Gamma] \rangle$   $a, b \in H^2(\Gamma, \mathbb{R})$  be the intersection form on  $\Gamma \backslash G/K$ . Define the linear functional  $T_\omega : H^2(\Gamma, \mathbb{Z}) \rightarrow \mathbb{R}$  as  $T_\omega(a) = Q(\omega, a)$ . Then we have:

**Theorem 2.17** *Let  $\Gamma$  be a discrete, torsion-free cocompact subgroup of  $\mathbf{SO}_0(1, 4)$  or of  $\mathbf{SU}(1, 2)$ , and  $\sigma$  be a multiplier of  $\Gamma$  such that  $\delta(\sigma) = 0$ . We assume also that  $\Gamma \backslash G/K$  is a spin manifold. Then the range of the trace map is*

$$[\text{tr}](K_0(C_r^*(\Gamma, \sigma))) = \mathbb{Z}\theta + \mathbb{Z} + B,$$

where  $2(2\pi)^2\theta = \langle [\omega \cup \omega], [\Gamma] \rangle$  is the result of pairing the cup product of multipliers  $[\omega \cup \omega]$  with the fundamental class of  $\Gamma$ , and  $B = \text{range}(T_\omega)$ .

### Proof.

We observe again that by the results of the previous subsection the twisted Kasparov map is an isomorphism. Therefore to compute the range of the trace map on  $K_0$ , it suffices to compute the range of the trace map on elements of the form

$$\mu_\sigma([\mathcal{E}^0] - [\mathcal{E}^1])$$

for any element

$$[\mathcal{E}^0] - [\mathcal{E}^1] \in K^0(\Gamma \backslash G/K).$$

where  $\mathcal{E}^0, \mathcal{E}^1$  are vector bundles over the compact manifold  $\Gamma \backslash G/K$ .

By the twisted  $L^2$  index theorem, Theorem 1.7, one has

$$[\text{tr}](\text{ind}_{(\Gamma, \sigma)}(\widetilde{\mathcal{D}}_{\mathcal{E}}^+ \otimes \nabla)) = \frac{1}{(2\pi)^2} \int_{\Gamma \backslash G/K} \widehat{A}(\Omega) \text{tr}(e^{R^{\mathcal{E}}}) e^\omega. \quad (2.12)$$

We next simplify the right hand side of equation (2.12) using

$$\begin{aligned} \widehat{A}(\Omega) &= 1 - \frac{1}{24} p_1(\Omega) \\ \text{tr}(e^{R^{\mathcal{E}}}) &= \text{rank } \mathcal{E} + \text{tr}(R^{\mathcal{E}}) + \frac{1}{2} \text{tr}(R^{\mathcal{E}})^2 \\ e^\omega &= 1 + \omega + \frac{1}{2}\omega^2. \end{aligned}$$

Therefore one has

$$\begin{aligned} [\text{tr}](\text{ind}_{(\Gamma, \sigma)}(\widetilde{\mathcal{D}}_{\mathcal{E}}^+ \otimes \nabla)) &= \frac{\text{rank } \mathcal{E}}{2(2\pi)^2} \int_{\Gamma \backslash G/K} \omega^2 \\ &+ \frac{1}{2(2\pi)^2} \int_{\Gamma \backslash G/K} \text{tr}(R^{\mathcal{E}})^2 - \frac{1}{24(2\pi)^2} \int_{\Gamma \backslash G/K} p_1(\Omega) + \frac{1}{(2\pi)^2} \int_{\Gamma \backslash G/K} \text{tr}(R^{\mathcal{E}}) \wedge \omega, \end{aligned}$$

Now by the Atiyah-Singer index theorem<sup>3</sup>, we see that

$$-\frac{1}{24(2\pi)^2} \int_{\Gamma \backslash G/K} p_1(\Omega) + \frac{1}{2(2\pi)^2} \int_{\Gamma \backslash G/K} \text{tr}(R^{\mathcal{E}})^2 = \text{index}(\mathcal{D}_{\mathcal{E}}^+) \in \mathbb{Z},$$

Therefore we see that

$$[tr](K_0(C_r^*(\Gamma, \sigma))) = \mathbb{Z}\theta + \mathbb{Z} + B,$$

$$\text{where } 2(2\pi)^2\theta = \int_{\Gamma \backslash G/K} \omega^2 \text{ and } B = \text{range}(T_\omega). \diamond$$

**Remarks 2.18** The spin hypothesis on  $\Gamma \backslash G/K$  can be easily replaced by  $\text{spin}^\mathbb{C}$ , without much alteration in the proof.

The proof of the following proposition is similar to that of Proposition 2.8 and we omit it.

**Proposition 2.19** *Let  $\Gamma$  be as in Theorem 2.17. Let  $\sigma$  be a multiplier on  $\Gamma$  such that  $\delta(\sigma) = 0$ . If  $\sigma$  defines a rational cohomology class, then there are at most a finite number of unitary equivalence classes of projections, other than 0 and 1, in the reduced twisted group  $C^*$ -algebra  $C_r^*(\Gamma, \sigma)$ .*

### 3. Applications to the spectral theory of projectively periodic elliptic operators and the classification of twisted group $C^*$ algebras

In this section, we apply the range of the trace theorem, to prove some qualitative results on the spectrum of projectively periodic self adjoint elliptic operators on the universal covering of a good orbifold, or what is now best known as non-commutative Bloch theory. In particular, we study generalizations of the hyperbolic analogue of the Ten Martini Problem in <sup>9</sup> and the Bethe-Sommerfeld conjecture. We also classify up to isomorphism, the twisted group  $C^*$  algebras for a cocompact Fuchsian group.

Let  $M$  be a compact, good orbifold, that is, the universal cover  $\Gamma \rightarrow \widetilde{M} \rightarrow M$  is a smooth manifold and we will assume as before that there is a  $(\Gamma, \bar{\sigma})$ -action on  $L^2(\widetilde{M})$  given by  $T_\gamma = U_\gamma \circ S_\gamma \forall \gamma \in \Gamma$ . Let  $\tilde{\mathcal{E}}$ ,  $\tilde{\mathcal{F}}$  be Hermitian vector bundles on  $M$  and let  $\tilde{\mathcal{E}}$ ,  $\tilde{\mathcal{F}}$  be the corresponding lifts to  $\Gamma$ -invariants Hermitian vector bundles on  $\widetilde{M}$ . Then there are  $(\Gamma, \sigma)$ -actions on  $L^2(\widetilde{M}, \tilde{\mathcal{E}})$  and  $L^2(\widetilde{M}, \tilde{\mathcal{F}})$  which are also given by  $T_\gamma = U_\gamma \circ S_\gamma \forall \gamma \in \Gamma$ .

Now let  $D : L^2(\widetilde{M}, \tilde{\mathcal{E}}) \rightarrow L^2(\widetilde{M}, \tilde{\mathcal{F}})$  be a self adjoint elliptic differential operator that commutes with the  $(\Gamma, \bar{\sigma})$ -action that was defined earlier. We begin with some basic facts about the spectrum of such an operator. Recall that the *discrete spectrum* of  $D$ ,  $\text{spec}_{disc}(D)$  consists of all the eigenvalues of  $D$  that have finite multiplicity, and the *essential spectrum* of  $D$ ,  $\text{spec}_{ess}(D)$  consists of the complement  $\text{spec}(D) \setminus \text{spec}_{disc}(D)$ . That is,  $\text{spec}_{ess}(D)$  consists of the set of accumulation points of the spectrum of  $D$ ,  $\text{spec}(D)$ . Our first goal is to prove that the essential spectrum is unbounded. Our proof will be a modification of an argument in <sup>35</sup>.

**Lemma 3.20** *Let  $D : L^2(\widetilde{M}, \tilde{\mathcal{E}}) \rightarrow L^2(\widetilde{M}, \tilde{\mathcal{F}})$  be a self adjoint elliptic differential operator that commutes with the  $(\Gamma, \bar{\sigma})$ -action. Then the discrete spectrum of  $D$  is empty.*

**Proof.** Let  $\lambda$  be an eigenvalue of  $D$  and  $V$  denote the corresponding eigenspace. Then  $V$  is a  $(\Gamma, \sigma)$ -invariant subspace of  $L^2(\widetilde{M}, \widetilde{\mathcal{E}})$ . If  $\mathcal{F}$  is a relatively compact fundamental domain for the action of  $\Gamma$  on  $\widetilde{M}$ , one sees as in section 1.2 that there is a  $(\Gamma, \bar{\sigma})$ -isomorphism

$$L^2(\widetilde{M}, \widetilde{\mathcal{E}}) \cong L^2(\Gamma) \otimes L^2(\mathcal{F}, \widetilde{\mathcal{E}}|_{\mathcal{F}})$$

Here the  $(\Gamma, \bar{\sigma})$ -action on  $L^2(\mathcal{F}, \widetilde{\mathcal{E}}|_{\mathcal{F}})$  is trivial, and is the regular  $(\Gamma, \bar{\sigma})$  representation on  $L^2(\Gamma)$ . Therefore it suffices to show that the dimension of *any*  $(\Gamma, \bar{\sigma})$ -invariant subspace  $V$  of  $L^2(\Gamma)$  is infinite dimensional. Let  $\{v_1, \dots, v_N\}$  be an orthonormal basis for  $V$ . Then one has

$$T_{\gamma} v_i(\gamma') = \sum_{j=1}^N U_{ij}(\gamma) v_j(\gamma') \quad \forall \gamma, \gamma' \in \Gamma$$

where  $U = (U_{ij}(\gamma))$  is some  $N \times N$  unitary matrix. Therefore

$$\begin{aligned} N = \sum_{j=1}^N \|v_i\|^2 &= \sum_{j=1}^N \sum_{\gamma \in \Gamma} |v_i(\gamma \gamma')|^2 \\ &= \sum_{\gamma \in \Gamma} \sum_{i=1}^N \sum_{j=1}^N \sum_{k=1}^N U_{ij}(\gamma) \overline{U_{ik}(\gamma)} v_j(\gamma') \overline{v_k(\gamma')} \\ &= \sum_{\gamma \in \Gamma} \sum_{j=1}^N |v_j(\gamma')|^2 \\ &= \#(\Gamma) \sum_{j=1}^N |v_j(\gamma')|^2. \end{aligned}$$

Since  $\#(\Gamma) = \infty$ , it follows that either  $N = 0$  or  $N = \infty$ .  $\diamond$

**Corollary 3.21** *Let  $D$  be as in Lemma 3.20 above. Then the essential spectrum of  $D$  coincides with the spectrum of  $D$ , and so it is unbounded.*

**Proof.** By the Lemma above, we conclude that  $\text{spec}_{ess}(D)$  and  $\text{spec}(D)$  coincide. Since  $D$  is an unbounded self-adjoint operator, it is a standard fact that  $\text{spec}(D)$  is unbounded cf.<sup>18</sup>, yielding the result.  $\diamond$

Note that in general the spectral projections of  $D$ ,  $E_{\lambda} \notin C^*(\sigma)$  (see section 1.2 for the definition). However one has

**Proposition 3.22 (Sunada, Brüning-Sunada)** *Let  $D$  be defined as in Lemma 3.20 above. If  $\lambda_0 \notin \text{spec}(D)$ , then  $E_{\lambda_0} \in C^*(\sigma)$ .*

**Proof.** Firstly, there is a standard reduction to the case when  $D$  is positive and of even order  $d \geq 2$  cf.<sup>8</sup>, so we will assume this without loss of generality. By a result of Greiner, see also Brüning-Sunada<sup>8</sup>, there are off diagonal estimates for the Schwartz kernel of the heat operator  $e^{-tD}$

$$|k_t(x, y)| \leq C_1 t^{-n/d} \exp\left(-C_2 d(x, y)^{d/(d-1)} t^{-1/(d-1)}\right)$$

for some positive constants  $C_1, C_2$  and for  $t > 0$  in any compact interval. Since the volume growth of a orbifold covering space is at most exponential, we see in particular that

$|k_t(x, y)|$  is  $L^1$  in both variable separately, so that

$$e^{-tD} \in C^*(\sigma).$$

Note that

$$\chi_{[0, e^{-t\lambda}]}(D) = \chi_{[0, \lambda]}(e^{-tD}).$$

Let  $t = 1$  and  $\lambda_1 = -\log \lambda_0$ . Then  $\lambda_1 \notin \text{spec}(e^{-D})$  and

$$\chi_{[0, \lambda_1]}(e^{-D}) = \phi(e^{-D})$$

where  $\phi$  is a compactly supported smooth function,  $\phi \cong 1$  on  $[0, \lambda_1]$  and  $\phi \cong 0$  on the remainder of the spectrum. Since  $C^*(\sigma)$  is closed under the continuous functional calculus, it follows that  $\phi(e^{-D}) \in C^*(\sigma)$ , that is  $E_{\lambda_0} \in C^*(\sigma)$ .  $\diamond$

Let  $D$  be any  $(\Gamma, \bar{\sigma})$ -invariant self-adjoint elliptic differential operator  $D$  on  $\widetilde{M}$ . Since the spectrum  $\text{spec}(D)$  is a closed subset of  $\mathbb{R}$ , its complement  $\mathbb{R} \setminus \text{spec}(D)$  is a countable union of disjoint open intervals. Each such interval is called a *gap* in the spectrum.

**Proposition 3.23** *Let  $\Gamma$  be a Fuchsian group of signature  $(g, \nu_1, \dots, \nu_n)$ . Let  $\sigma$  be a multiplier on  $\Gamma$  such that  $\delta(\sigma) = 0$ , and  $2\pi\theta = \langle [\sigma], [\Gamma] \rangle \in (0, 1]$  be the result of pairing the cohomology class of  $\sigma$  with the fundamental class of  $\Gamma$ . If  $\theta$  is rational, then the spectrum of any  $(\Gamma, \bar{\sigma})$ -invariant self-adjoint elliptic differential operator  $D$  on  $\widetilde{M}$  has only a finite number of gaps in the spectrum in every half line  $(-\infty, \lambda]$ . Here  $\Gamma \rightarrow \widetilde{M} \rightarrow M$  is the universal orbifold covering of a compact good orbifold  $M$  with orbifold fundamental group  $\Gamma$ . In particular, the intersection of  $\text{spec}(D)$  with any compact interval in  $\mathbb{R}$  is never a Cantor set.*

**Proof.** We first observe that by equation 1.2 in section 1.2, one has  $C^*(\sigma) \cong C_r^*(\Gamma, \sigma) \otimes \mathcal{K}$ . By Proposition 2.16 and Theorem 2.15, it follows that one has the estimate  $C_\sigma(\Gamma) \geq 1/q > 0$  for the Kadison constant in this case. Then one applies Theorem 1 in Brüning-Sunada<sup>8</sup> to deduce the proposition.  $\diamond$

In words, we have shown that whenever the multiplier is rational, then the spectrum of a projectively periodic elliptic operator is the union of countably many (possibly degenerate) closed intervals, which can only accumulate at infinity.

Recall the important  $\Gamma$ -invariant elliptic differential operator, which is the Schrödinger operator

$$H_V = \Delta + V$$

where  $\Delta$  denotes the Laplacian on functions on  $\widetilde{M}$  and  $V$  is a  $\Gamma$ -invariant function on  $\widetilde{M}$ . It is known that the Baum-Connes conjecture is true for all amenable discrete subgroups of a connected Lie group and also for discrete subgroups of  $\mathbf{SO}(n, 1)$ , see<sup>23</sup> and  $\mathbf{SU}(n, 1)$ , see<sup>22</sup>. For all these groups  $\Gamma$ , it follows that the Kadison constant  $C_1(\Gamma)$  is positive. Therefore we see by the arguments above that the spectrum of the periodic elliptic operator  $H_V$  is the union of countably many (possibly degenerate) closed intervals, which can only accumulate at infinity. This gives evidence for the following:

**Conjecture 1 (The Generalized Bethe-Sommerfeld conjecture)** *The spectrum of any  $\Gamma$ -invariant Schrödinger operator  $H_V$  has only a finite number of bands, in the sense that the intersection of the resolvent set with  $\mathbb{R}$  has only a finite number of components.*

We remark that the Bethe-Sommerfeld conjecture has been proved completely by Skriganov<sup>39</sup> in the Euclidean case.

This leaves open the question of whether there are  $(\Gamma, \bar{\sigma})$ -invariant elliptic differential operators  $D$  on  $\mathbf{H}$  with Cantor spectrum when  $\theta$  is irrational. In the Euclidean case, this is usually known as the *Ten Martini Problem*, and is to date, not completely solved, though much progress has been made<sup>38</sup>. We pose a generalization of this problem to the hyperbolic case (which also includes the Euclidean case):

**Conjecture 2 (The Generalized Ten Dry Martini Problem)** *Suppose given a multiplier  $\sigma$  on  $\Gamma$  such that  $\delta(\sigma) = 0$ , and let  $2\pi\theta = \langle [\sigma], [\Gamma] \rangle \in (0, 1]$  be the result of pairing the cohomology class of  $\sigma$  with the fundamental class of  $\Gamma$ . If  $\theta$  is irrational, then there is a  $(\Gamma, \bar{\sigma})$ -invariant elliptic differential operator  $D$  on  $\mathbf{H}$  which has a Cantor set type spectrum, in the sense that the intersection of  $\text{spec}(D)$  with some compact interval in  $\mathbb{R}$  is a Cantor set.*

### 3.1. The four-dimensional case

The spectral properties studied in this section do not represent a purely two-dimensional phenomenon. In fact, it is possible to derive similar results in higher dimensions, as the following example shows.

**Proposition 3.24** *Let  $\Gamma$  be a discrete, torsion-free cocompact subgroup of  $\mathbf{SO}_0(1, 4)$  or of  $\mathbf{SU}(1, 2)$ , and  $\sigma$  be a multiplier of  $\Gamma$  such that  $\delta(\sigma) = 0$ . We assume also that  $\Gamma \backslash G/K$  is a spin manifold. If  $[\omega] \in H^2(M, \mathbb{R})$  is a rational cohomology class, then the spectrum of any  $(\Gamma, \bar{\sigma})$ -invariant self-adjoint elliptic differential operator  $D$  on  $M$  has only a finite number of gaps in the spectrum in every half line  $(-\infty, \lambda]$ . In particular, the intersection of  $\text{spec}(D)$  with any compact interval in  $\mathbb{R}$  is never a Cantor set.*

**Proof.** By Proposition 2.19 and Theorem 2.17, it follows that one has the estimate  $C_\sigma(\Gamma) \geq 1/q > 0$  for the Kadison constant in this case. Then one applies Theorem 1 in Brüning-Sunada<sup>8</sup> to deduce the proposition.  $\diamond$

### 3.2. On the classification of twisted group $C^*$ -algebras

We will now use the range of the trace theorem 2.15, to give a complete classification, up to isomorphism, of the twisted group  $C^*$ -algebras  $C^*(\Gamma, \sigma)$ , where  $\Gamma$  is a Fuchsian group of signature  $(g, \nu_1, \dots, \nu_n)$  and we assume as before that  $\delta(\sigma) = 0$ .

**Proposition 3.25 (The isomorphism classification of twisted group  $C^*$ -algebras)** Let  $\sigma, \sigma' \in H^2(\Gamma, \mathbb{R}/\mathbb{Z})$  be multipliers on  $\Gamma$  satisfying  $\delta(\sigma) = 0 = \delta(\sigma')$ , and

$$2\pi\theta = \langle \sigma, [\Gamma] \rangle \in (0, 1], \quad 2\pi\theta' = \langle \sigma', [\Gamma] \rangle \in (0, 1]$$

be the result of pairing  $\sigma, \sigma'$  with the fundamental class of  $\Gamma$ . Then  $C^*(\Gamma, \sigma) \cong C^*(\Gamma, \sigma')$  if and only if

$$\theta' \in \left\{ \left( \theta + \sum_{i=1}^n \beta_i/\nu_i \right) \bmod 1, \left( 1 - \theta + \sum_{i=1}^n \beta_i/\nu_i \right) \bmod 1 \right\},$$

where  $0 \leq \beta_i \leq \nu_i - 1 \quad \forall i = 1, \dots, n$ .

**Proof.** Let  $tr$  and  $tr'$  denote the canonical traces on  $C^*(\Gamma, \sigma)$  and  $C^*(\Gamma, \sigma')$  respectively. Let

$$\phi : C^*(\Gamma, \sigma) \cong C^*(\Gamma, \sigma')$$

be an isomorphism, and let

$$\phi_* : K_0(C^*(\Gamma, \sigma)) \cong K_0(C^*(\Gamma, \sigma'))$$

denote the induced map on  $K_0$ . By Theorem 2.15, the range of the trace map on  $K_0$  is

$$[tr](K_0(C^*(\Gamma, \sigma))) = \mathbb{Z}\theta + \mathbb{Z} + \sum_{i=1}^n \mathbb{Z}(1/\nu_i)$$

and

$$[tr'](K_0(C^*(\Gamma, \sigma'))) = \mathbb{Z}\theta' + \mathbb{Z} + \sum_{i=1}^n \mathbb{Z}(1/\nu_i).$$

Therefore if  $\theta$  is irrational, then

$$\mathbb{Z}\theta + \mathbb{Z} + \sum_{i=1}^n \mathbb{Z}(1/\nu_i) = \mathbb{Z}\theta' + \mathbb{Z} + \sum_{i=1}^n \mathbb{Z}(1/\nu_i)$$

implies that  $\theta'$  is also irrational and that

$$\theta \pm \theta' \in \mathbb{Z} + \sum_{i=1}^n \mathbb{Z}(1/\nu_i).$$

Since  $\theta, \theta' \in (0, 1]$ , one deduces that

$$\theta' \in \left\{ \left( \theta + \sum_{i=1}^n \beta_i/\nu_i \right) \bmod 1, \left( 1 - \theta + \sum_{i=1}^n \beta_i/\nu_i \right) \bmod 1 \right\},$$

where  $0 \leq \beta_i \leq \nu_i - 1 \quad \forall i = 1, \dots, n$ . Virtually the same argument holds when  $\theta$  is rational, but one argues in  $K$ -theory first, and applies the trace only at the final step.

First observe that a diffeomorphism  $C : \Sigma_{g'} \rightarrow \Sigma_{g'}$  lifts to a diffeomorphism  $C'$  of  $\mathbf{H}$  such that  $C'\Gamma C'^{-1} = \Gamma$ , i.e. it defines an automorphism of  $\Gamma$ . Recall that the finite group

$$G = \{C_i : C_i^{\nu_i} = 1 \quad \forall i = 1, \dots, n\}$$

acts on  $\Sigma_{g'}$  with quotient  $\Sigma(g, \nu_1, \dots, \nu_n)$ . By the observation above, we see that  $G$  also acts as automorphisms of  $\Gamma$ . Now  $C_i[\Gamma] = \lambda_i[\Gamma]$ , where  $\lambda_i \in \mathbb{C}$ . Since  $C_i C_j[\Gamma] = \lambda_i \lambda_j[\Gamma]$  and  $C_i^{\nu_i} = 1$ , it follows that  $\lambda_i$  is an  $\nu_i^{th}$  root of unity, i.e.  $\lambda_i = e^{2\pi\sqrt{-1}(1/\nu_i)}$ . Let  $C \in G$ , i.e.  $C = \prod_{i=1}^n C_i^{\beta_i}$ . We evaluate

$$\langle C^*[\sigma], [\Gamma] \rangle = \langle [\sigma], C_*[\Gamma] \rangle = \langle \left[ \prod_{i=1}^n \lambda_i^{\beta_i} \sigma \right], [\Gamma] \rangle = \theta + \sum_{i=1}^n \beta_i / \nu_i.$$

As in section 2.1 we see that

$$C^*[\sigma] = \left[ \prod_{i=1}^n \lambda_i^{\beta_i} \sigma \right] \in \ker \delta \subset H^2(\Gamma, \mathbf{U}(1)).$$

Therefore the automorphism  $C_*$  of  $\Gamma$  induces an isomorphism of twisted group  $C^*$ -algebras

$$C^*(\Gamma, \sigma) \cong C^*(\Gamma, C^*\sigma) \cong C^*(\Gamma, \lambda\sigma).$$

where  $\lambda = \prod_{i=1}^n \lambda_i^{\beta_i}$ .

Now let  $\psi : \Sigma_{g'} \rightarrow \Sigma_{g'}$  be an orientation reversing diffeomorphism. Then as observed earlier,  $\psi$  induces an automorphism  $\psi_* : \Gamma \rightarrow \Gamma$  of  $\Gamma$ . We evaluate

$$\langle \psi^*[\sigma], [\Gamma] \rangle = \langle [\sigma], \psi_*[\Gamma] \rangle = \overline{\langle [\sigma], [\Gamma] \rangle} = \langle [\bar{\sigma}], [\Gamma] \rangle,$$

since  $\psi$  is orientation reversing. As in section 2.1 we see that  $\psi^*[\sigma] = [\bar{\sigma}] \in \ker \delta \subset H^2(\Gamma, \mathbf{U}(1))$ . Therefore the automorphism  $\psi_*$  of  $\Gamma$  induces an isomorphism of twisted group  $C^*$ -algebras

$$C^*(\Gamma, \sigma) \cong C^*(\Gamma, \psi^*\sigma) \cong C^*(\Gamma, \bar{\sigma}).$$

Therefore if  $\theta' \in \{(\theta + \sum_{i=1}^n \beta_i / \nu_i) \pmod{1}, (1 - \theta + \sum_{i=1}^n \beta_i / \nu_i) \pmod{1}\}$ , where  $0 \leq \beta_i \leq \nu_i - 1 \quad \forall i = 1, \dots, n$ , one has  $C^*(\Gamma, \sigma) \cong C^*(\Gamma, \sigma')$ , completing the proof of the proposition.  $\diamond$

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